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Climate and Land-Use Change Effects on Ecological Resources in Three Watersheds: A Synthesis Report

National Center for Environmental Assessment
Office of Research and Development

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A Synthesis Report

Global Change Research Program
National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

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ABSTRACT

During the early 2000s, the Environmental Protection Agency's (EPA's) Office of Research and Development, Global Change Research Program, supported three watershed assessments to evaluate different approaches and tools for understanding and managing climate and land-use change impacts on watershed ecological resources. Watershed assessments were conducted for (1) several small rivers in southern Maryland, (2) Arizona's San Pedro River, and (3) California's Sacramento River. In this report, we comparatively analyze the three case-study approaches in order to develop recommendations that may be useful as guidance to others conducting similar assessments. Key insights gained from these studies include:

1. Prioritize locations for studies to maximize decision support.
2. Target selection of stakeholders, establish credibility of underlying methods and models, and incorporate incentives for mutually beneficial results.
3. Provide essential climate science capabilities and tools to project teams.
4. Develop model linkages at the onset, carry out assessment activities at multiple scales, and require explicit uncertainty analysis of results.

The watershed assessment case studies described in this report yield richness of detail in terms of methods and results, as well as inform more generally on best practices for conducting future watershed assessments. However these were pioneering studies addressing difficult and complex problems. Future assessments will continue to refine the understanding of how to maximize decision support, including providing necessary keystone capabilities and tools to effectively estimate climate change vulnerabilities, developing and supporting successful

stakeholder processes, and characterizing uncertainty and scaling or transferring results to increase their relevance.

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Cover Photo of Patapsco River in the spring, courtesy of the Chesapeake Bay Program (www.chesapeakebay.net).

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LIST OF ABBREVIATIONS AND ACRONYMS

A2	medium-high
B2	medium-low
BLM	Bureau of Land Management
EPA	Environmental Protection Agency
FIF	forecasted indices for fish
GCM	General Circulation Model
GCRP	Global Change Research Program
HadCM3	Hadley Centre Model v3
HSI	Habitat Suitability Index
NCEA	National Center for Environmental Assessment
ORD	Office of Research and Development
PCM	Parallel Climate Model
SAHRA	semi-arid hydrology and riparian areas
SI	suitability index
SPRNCA	San Pedro Riparian National Conservation Area
SWAT	Soil Water Assessment Tool
USFWS	U.S. Fish and Wildlife Service
USPP	Upper San Pedro Partnership
WEAP	Water Evaluation and Planning

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EXECUTIVE SUMMARY

During the early 2000s, the Environmental Protection Agency's (EPA's) Office of Research and Development, Global Change Research Program, supported three watershed assessments to evaluate different approaches and tools for understanding and managing climate and land-use change impacts on watershed ecological resources. These were pioneering studies intended not only to provide useful information in study watersheds but also to advance EPA's general understanding of the conduct and use of impact assessments of this type to support management decision making. Watershed assessments were conducted by three independent case-study teams of scientists for: (1) several small rivers in southern Maryland, (2) Arizona's San Pedro River, and (3) California's Sacramento River. Although the overarching goal of each assessment was the same—advance our understanding of the conduct of impacts assessments—the specific focus, scale, methods, and models of each differed based on priorities identified by each project team. Detailed results of these studies have been published elsewhere. In this report, we comparatively analyze the three case-study approaches in order to develop recommendations that may be useful as guidance to others conducting similar assessments. Specifically, each watershed assessment was evaluated to determine the following: the extent to which results obtained in each assessment may apply to similar systems; whether the methods used to consider the implications of climate change for ecosystem processes at the watershed scale may be useful for other project teams and in other geographic regions of the country; and whether the insights gained about the assessment process will be helpful to other researchers seeking to produce useful climate impacts information for decision makers.

MARYLAND CASE STUDY

The specific goal of the Maryland case study was to better understand how the effects of climate variability and change on stream ecosystems depend on land-use choices in surrounding areas. The interaction of climate and land-use change is important in the context of regional planning and adaptation to climate change. The Maryland case-study team developed and applied a model, the Forecasted Indices for Fish (FIF), to assess the combined effects of land-use change and climate change on stream fish assemblages over the next century. The scenarios of future change used in their analyses were the following: (1) baseline scenario (low urbanization;

no new construction; and present-day climate), (2) baseline scenario with urbanization (higher impervious surface, lower forest cover, significant construction activity), (3) four future climate change scenarios—based on projections from the Hadley CM3 and Parallel Climate Models (PCM) under medium-high (A2) and medium-low (B2) emissions scenarios, and (4) the same four climate change scenarios plus urbanization.

Four pathways were examined by which urbanization and climate change are likely to directly and indirectly affect fish reproduction and growth—spawning temperatures, spawning substrate, juvenile growth, and adult growth. Modeling results showed that urbanization alone affected growth or reproduction only slightly, suppressing these functions in 8 of 39 fish species. However, climate change alone depressed these functions in 22−29 species. The combination of both stressors usually increased the number of stressed species, sometimes to a considerable degree. Under all of these scenarios, substantial changes in fish assemblage composition are anticipated, including loss of diversity.

Urban growth and its interaction with climate change could dramatically affect ecosystem structure and services through impacts to headwater streams. While mitigating the causes of climate change itself may not be addressed at the local scale to a significant degree, the Maryland case-study team concluded that stream impacts may be reduced through decisions made about how land uses change in the future.

Models and results could be applied to other Piedmont streams for hydrologic changes, and other watersheds of the U.S. East Coast with similar species mixes for the fish assemblage results (using models reparameterized with local data). For streams with different fish assemblages, it might be possible to develop a similar model if local data are available on food resources and on the recruitment, growth, and survival of the species of interest.

SAN PEDRO CASE STUDY

The goal of the San Pedro case study was to determine the likely coupled effects of climate change, urbanization, and groundwater withdrawals on ecological resources and biodiversity in the San Pedro Riparian National Conservation Area. This information is important to aid in managing development and hydrologic conditions in this area.

Five future climate change scenarios were evaluated: (1) baseline (no climate change), (2) warmer (progressive temperature warming over 100 years, with a 4°C increase in maximum daily temperature and a 6°C increase in minimum daily temperature by 2102), (3) warmer and dryer (same progressive temperature warming as the warm scenario and a progressive decline in winter daily precipitation of 50% by 2102), (4) warmer and wetter (same progressive temperature warming as the warm scenario with a progressive increase in winter daily precipitation of 50% by 2102), and (5) warmer and very wet (same progressive temperature warming as the warm scenario with a progressive increase in winter daily precipitation of 100% by 2102).

The San Pedro case-study team analyzed species, vegetation, and habitat suitability first, and then developed a model linking vegetation, groundwater, and surface water to tie the fluctuations in groundwater levels to evapotranspiration. Simulations using this model showed that altered hydrology resulting from climate change would fragment existing riparian and wetland communities and lead to their replacement by more mesic or xeric communities (i.e., vegetation more typical of the desert matrix). The influence of climate change on pioneer riparian communities depended on the magnitude and direction of precipitation changes: less winter precipitation would result in fewer winter floods, lower rates of channel migration, and much lower cottonwood and willow recruitment rates; increased winter precipitation would result in larger and more frequent winter floods, higher channel migration rates, and higher cottonwood and willow recruitment rates.

The San Pedro case-study team also determined that avian biodiversity would be affected by climate change, with some of the most abundant bird species being the most adversely affected by changes in the vegetative community. Results from the three driest climate scenarios suggested that the gallery forest would be fragmented or nonexistent and would result in biodiversity loss and a likely drop in ecotourism. However, results from the warmer and wetter scenario suggested that the water supply to the ecosystem would be adequate enough to maintain ecosystem services and ecotourism.

Results from this case study, and, in particular, the challenges of aquifer depletion were applicable to other areas. The vegetation, hydrology, and wildlife data inputs used in the models made them specific to the Southwestern United States and other arid environments with groundwater-dependent riparian systems. The channel migration model was useful in other regions, as long as the specific vegetation data inputs were adapted; however, the approach was not applicable to systems where vegetation uses water from the unsaturated zone.

SACRAMENTO CASE STUDY

The focus of the Sacramento case study was to assess how global change (climate and land-use change) would alter water supply, and how water supply and demand changes would interact to affect offstream water uses for agriculture and instream flows for Chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento Basin. The assessment was conducted using an integrated decision support tool, the Water Evaluation and Planning (WEAP) modeling system, to link climate and land-use/land-cover conditions with watershed conditions, water supply and anticipated demands, ecosystem needs, infrastructure, the regulatory environment, and water management options.

Four future climate change scenarios were evaluated based on downscaled output from two General Circulation Models (GCMs) (PCM and Geophysical Fluid Dynamics Laboratory, and two greenhouse gas emissions scenarios [A2 and B1]). Two of the four scenarios resulted in decreasing precipitation over the next century. The two remaining scenarios showed less pronounced precipitation changes. All four scenarios projected increases in average winter and summer temperatures over the next century ranging from a lower bound increase of 1.5ºC in winter and 1.4ºC in summer to the higher bound of 3.0ºC in winter and 5.0ºC in summer.

All four climate change scenarios resulted in reductions in water availability, with large impacts on supply at the end of the 100-year simulations. Reservoir levels were much lower in the late summer and early fall, and groundwater pumping increased. The Sacramento River's water temperature regime was altered, leading to further reductions in habitat for Chinook salmon due to exceedances of critical spawning and rearing temperatures. Management measures, such as improving irrigation efficiency and changing cropping patterns, resulted in a decline in water supply requirements. Managing the releases of cold water stored in reservoirs alleviated some of the future impacts of climate change on habitat for Chinook salmon.

The modeling framework used in this case study, WEAP, was developed specifically to be applied in other locations. The insights gained from this case study may also be applicable in a qualitative sense to other watersheds of similar character and nature: For example, areas where water supply is fully subscribed among users and climatic changes will require an understanding of the types of tradeoffs that may be required in the future—but the specific quantitative results would not be transferable.

FINDINGS AND RECOMMENDATIONS

The conduct and results of these three assessments suggest a number of conclusions concerning methodological advances, lessons learned, and other insights that might be useful guidance to others conducting similar assessments. They are provided to add to the body of literature and general wisdom that continues to grow regarding how to conduct assessments that provide actionable results. The following is a summary of key insights gained from these studies.

Prioritize Alternative Study Locations to Maximize Decision Support

One way to prioritize alternative study locations is to consider whether decisions are being made in that location that are sensitive to climate change, and whether information relevant to climate-sensitive decisions can be provided by the project team. To assess feasibility of producing good science and sound decision support, the project team should consider the resolution of the climate change data and the scale at which watershed-level information are available along with the scale at which key endpoints of the decisions at hand have to be assessed and the uncertainty introduced by bridging the gap. Assessment usefulness might also be strengthened by building in consideration of the study design to allow extrapolation of methods, models, or results to other locations across the country to inform broader audiences of decision makers.

Target Selection of Stakeholders, Establish Credibility, and Incorporate Incentives for Mutually Beneficial Results

Stakeholder engagement is an extremely important but potentially difficult and time-consuming task. The case studies described in this report suggest that stakeholder relationships may not need to extend to all potentially interested members of the lay public. Rather, The best strategy may be to target only specific decision makers with a clear stake in the study’s goals. For these targeted stakeholders, project teams should consider how to demonstrate the credibility of the science underlying their methods and models because the public debate on climate science has been polarizing, and its relevance to issues on the ground difficult to discern for the average person. To maintain stakeholder processes throughout the project lifetime, case-study teams need to empower and motivate them to participate. Elements of empowerment and motivation include ensuring transparency of the work and communicating results often, remaining flexible in the assessment process to incorporate feedback from stakeholders in the analysis, recognizing and rewarding stakeholder contributions to an assessment, developing and tracking factors to identify and institutionalize those factors that ensure and enhance stakeholder engagement, and providing technical assistance to build capacity at the local level to refine analyses with new information and evaluate effectiveness of adaptation responses over time.

Provide Keystone Climate Science Capabilities and Tools to Project Teams

Organizations considering supporting climate change assessments should consider whether to provide expertise to project teams to aid in selecting, interpreting, and downscaling GCM output (or otherwise incorporating climate change information into the assessment). Choosing among different combinations of emission scenarios and climate sensitivities and different methods of downscaling GCM output can be both daunting and resource intensive. Additional tools may also be provided, such as statistical techniques to evaluate trends in climate and hydrologic variables to complement GCM output. If climate change assessments are to be a core task of an organization, then building capacity in keystone skills or offering tools to project teams in areas such as climate scenario development, habitat suitability analysis, stakeholder facilitation, and uncertainty analysis and communication should be considered.

Emphasize Model Linkages, Carry Out Assessment Activities at Multiple Scales, and Require Explicit Uncertainty Analysis

For any climate change impact assessment, spending sufficient time in the beginning of the design process to clearly define inputs, outputs, and interactions among submodels may help to avoid scale-related integration issues that arise later when conducting the assessment. In the design process, consideration should also be given to whether different spatial scales of analysis are required to reliably address key decision endpoints when scale-dependent processes and cross-scale effects are involved. Finally, the inclusion of explicit methods to characterize and communicate uncertainty in the assessment design is critical to both the production of scientifically credible results and to the appropriate use of those results in decision making. Many techniques are available for watershed assessments that range from quantitative to qualitative. Providing uncertainty information allows more complete consideration of the potential range of outcomes and their implications and tradeoffs among alternative decisions.

The watershed assessment case studies described in this report yield richness of detail in terms of methods and results, as well as inform more generally on best practices for conducting future watershed assessments. We hope that the results presented here will contribute to developing a foundation for a long-term strategy for providing effective decision support. It must be noted, however, that these were pioneering studies addressing difficult and complex problems. As such, these studies and the lessons learned that are presented in this report represent only a single step forward in what is sure to be an ongoing process of experimentation and learning. Future assessments will continue to refine the understanding of how to maximize decision support, including providing necessary keystone capabilities and tools to effectively estimate climate change vulnerabilities, developing and supporting successful stakeholder processes, and characterizing uncertainty and scaling or transferring results to increase their relevance.

1. INTRODUCTION

1.1. PURPOSE OF THE REPORT

The effects of global change drivers differ by place and in scale, necessitating place-specific impacts information to enable stakeholders to respond appropriately. Place and scale also determine appropriate adaptation strategies and expected outcomes. This report is a synthesis of three watershed case-study assessments conducted by the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development (ORD), Global Change Impacts and Adaptation Program (GCIA) to advance the capability of managers to consider climate and land-use change in watershed management decisions. Rather than presenting methodological details, the purpose of this synthesis report is to highlight important findings.

The watershed case studies were initiated in 2002 to better understand the effects of global change on aquatic ecosystems within watersheds and to build capacity at appropriate levels of decision making to respond to these effects. The studies focused on key ecosystem services provided by the watersheds under study. Ecosystem services are the physical and biological functions performed by natural resources and the human benefits derived from those functions. Examples include water storage and delivery, water purification, habitat for species, and recreational opportunities that help promote human well-being. An advantage of focusing on ecosystem services is that they are "cross-cutting" indicators of ecological conditions that can be readily communicated to diverse stakeholders. A focus on services also makes it possible to concentrate a large amount of ecological data into a limited number of variables that are directly relevant to environmental decision making.

The case studies yielded valuable scientific understanding and provided important lessons about assessment and stakeholder processes. In this report, we set out to document those results, findings, and lessons learned across case studies in order to inform future watershed assessments. The remainder of Chapter 1 provides a more detailed introduction to the three watershed case studies that were conducted. Chapter 2 describes the assessment methods used by the case-study teams and key results, emphasizing those that are applicable elsewhere and those that support decision making to adapt to climate change. Chapter 3 provides a discussion of the findings and recommendations derived from those case studies, including insights gained from looking across all of the studies, and Chapter 4 summarizes the conclusions and implications for future watershed assessments.

The watershed case-study assessments were conducted by three EPA-funded research teams. National Center for Environmental Assessment (NCEA) GCIA Program provided technical direction to each project team and contributed directly to the synthesis results presented in this report. Additional support with this synthesis was provided by ICF International. The locations selected for the case studies are the San Pedro River watershed led by the American Bird Conservancy, the Sacramento River watershed led by the Tellus Institute, and watersheds in the Washington, D.C. metropolitan area conducted by the University of Maryland. We established criteria prior to the selection of these locations, including having a diversity of geographic regions and river ecosystem types represented, different land-use pressures (e.g., agricultural pressures, urban growth pressures), different future climate-induced changes (e.g., increased versus decreased streamflow), and different highly valued ecosystem services. This synthesis is based on each case-study team's scientific publications, final reports, an expert meeting of team members held toward the end of their assessment process, and a series of interviews conducted at the conclusion of the projects. The questions to which they responded in the interviews are the following:

1. What are the major methodological advances developed in your case study?
2. What is the applicability of the methodologies that you employed to other watersheds? Is applicability tied to scale, assessment endpoints, regions, or some other factor(s)?
3. What do you regard as the most important/interesting results?
4. To what extent do the case-study findings apply to other watersheds? Is applicability tied to scale, assessment endpoints, regions, or some other factor(s)?
5. To what extent could the outputs of your project support decisions, and what types of decisions are they? More specifically, would your results affect watershed management practices, and if so, how? If you suspect they won't, what are the obstacles, if any?
6. To what extent did you isolate land-use change and climate change as driving factors, and what were the results?

7. If you were to propose additional work, what do you think the next phase of the project should entail? What steps would be natural extensions of the work that has already been done?
8. What do you consider to be the most important lessons learned or recommendations for future watershed assessments?

The remainder of this chapter provides more detail on the criteria for case-study design and selection and a brief introduction to the case studies themselves.

1.2. THE CASE STUDIES

1.2.1. Motivation for the Watershed Case Studies

The Global Change Research Act of 1990 established the U.S. Global Change Research Program (USGCRP) to coordinate a comprehensive, multiagency research program on global change. As a member of the USGCRP, the ORD conducts research and assessments that examine the effect of climate, land use, and other factors on aquatic ecosystems and providing decision support resources and adaptation options to stakeholders.

NCEA GCIA initiated watershed case studies to gain a better understanding of the effects of global change on aquatic ecosystems and water quality, and to build capacity to respond to these effects at appropriate levels of decision making. That led to the choice of case-study sites that differed hydrologically and bioclimatically from each other. The studies were also in different regions, including the Western United States, the arid/semiarid Southwest, and the Eastern United States. We chose to focus at the watershed scale based on the knowledge that the properties of aquatic systems are strongly influenced by the surrounding land and are often managed and analyzed as a component of a larger watershed. The case-study approach stems from a motivation to conduct assessments that fit into the existing watershed-based strategy used by U.S. water management programs to integrate water management activities within hydrologically defined drainage basins or watersheds. Additionally, NCEA GCIA has historically had a program-wide emphasis on examining site- or region-specific impacts and adaptation measures.

The assessment approach used for each case study integrates methods and concepts of ecological risk assessment, ecosystem services, scenario analysis, and stakeholder engagement processes. The design of the case studies was guided by EPA's ecological risk assessment framework (U.S. EPA, 1998). Climate change scenarios are used in conjunction with scenarios of other relevant global change stressors and quantitative and conceptual models to examine the potential impacts of global change on aquatic ecosystems. Therefore, the following list of desired case-study design elements were identified prior to selecting the case-study sites:

- Address the combined impacts of climate change with other stressors, especially land-use change. Over the past century, there has been a trend for a higher proportion of precipitation to fall in intense events (e.g., more than 2 inches per event), and these intense events contribute to nonpoint source pollution (Karl and Knight, 1998). Climate change is anticipated to amplify this effect. Land use change (especially urbanization) modifies stream hydrology by affecting the proportion of precipitation that immediately enters the stream as runoff, and, thus, can also result in a "flashier" flow pattern (or hydrograph) (Karl and Knight, 1998). The case studies were designed to examine these (and other) interactions.

- Emphasize ecosystem services. The concept of ecosystem services enables individuals from a cross section of society to express the values they hold for ecological processes or functions using a common language that helps frame assessment questions relevant to decision making. Most of the watershed management decisions address a subset of ecosystem services that aquatic systems provide. These services—which include water supply, hydropower, recreational amenities, habitat for species, and transportation—are the amenities that motivate stakeholders. Thus, the case studies attempted to identify assessment endpoints that relate to these services.

- Involve stakeholders. The goals of an assessment are to communicate insights about the possible consequences of global change and the potential for adaptive responses. Stakeholder involvement is crucial throughout this process to ensure that the assessment is timely and relevant, and that results are communicated effectively.

- Use a risk assessment approach. Consistent with the human health and ecological risk assessment programs within ORD, we applied EPA's ecological risk assessment paradigm (U.S. EPA, 1998) to our global change assessments. The case studies were thus designed to clearly articulate the problem and develop an analysis plan (problem formulation), conduct an exposure assessment, effects assessment, and risk characterization, and to use best practices to produce high-quality scientific results. Watershed assessments employ a modification of the strict exposure-effects approach because multiple stressors are being examined. Climate and land-use scenarios are intended to serve as exposure scenarios in order to project a range of potential effects.

With these design elements serving as the genesis for the effort, EPA formulated the problem that the case studies would address and selected a portfolio of three case studies.

1.2.2. Criteria for Selecting Case Studies

The goal of the case studies was to build capacity at appropriate levels of decision making to assess and respond to potential global change impacts on aquatic ecosystems within watersheds. The scientifically complex environmental problems associated with global change are beginning to be addressed under circumstances of increasingly complicated decision-making processes. Watershed management has become a process of balancing multiple objectives, such as drought and flood protection, habitat and species protection, and provision of adequate supplies of water for withdrawals for municipal, industrial, and agricultural uses. Waters and watersheds increasingly are seen as complex systems comprising both ecological and human processes (Webler and Tuler, 1999). Undertaking a set of watershed case studies enabled us to do an integrated examination of the processes of interest at scales that are amenable to decision making and scientific analysis.

Criteria used to evaluate and select the three watershed case studies were the following:

- The set of sites chosen should represent different geographic scales of a watershed system with respect to ecosystem services and stakeholders, different climate regimes, different land-use pressures, and different vulnerabilities and intensities of use in the context of a variety of current/existing stressors.
- Each site chosen should have services that are highly valued by the local community (and beyond the local community, if possible).
- Because of limited resources, gathering original data was beyond the capability of the NCEA GCRP. Therefore, sites chosen needed to have fairly detailed and comprehensive data sets already available. Supporting research conducted in the selected location(s) was considered an additional benefit.

1.2.3. The Portfolio of Case Studies

Three case-study locations were chosen based on the above criteria. The selected case-study sites were from diverse geographic regions and aquatic ecosystem types, with different land-use pressures (e.g., agricultural pressures, urban growth pressures) and different future climate-induced changes (e.g., increased versus decreased runoff). Each site provided highly valued ecosystem services and had substantial amounts of data and existing research on which the case-study teams were able to build. Table 1 provides a comparison of some of the key aspects of each of the case studies, and Figure 1 shows the location of the case studies across the

United States.

The Maryland case study focused on riverine systems and their associated riparian zones in four selected watersheds of the greater Washington, DC, metropolitan area. Ecosystem services of interest involved the maintenance of water quality, fish and invertebrate species, and primary production and the availability of detritus. Primary stressors of concern include climate change and land-use change, specifically disturbances resulting from urbanization, increasing imperviousness in watersheds, and destruction of streamside vegetation.

The San Pedro case study was located in the Upper San Pedro River riparian ecosystem in southeastern Arizona and northern Sonora, Mexico. This area supports a riparian ecosystem that maintains biodiversity at the ecotone between the Sonoran and Chihuahuan deserts and the plains grassland. The area contains one of the richest assemblages of species and supports one of the most important migratory bird habitats in western North America. The ecosystem services of interest thus included avian habitat suitability. Primary stressors of concern include groundwater pumping, climate change, and population growth.

The Sacramento case study was located in the Central Valley of California from the headwaters of the San Joaquin River in the south to the headwaters of the Sacramento River in the north. The area’s ecosystem services that were the focus of study included the provision of water for agriculture and instream habitat for Chinook salmon (*Oncorhynchus tshawytscha*). The Central Valley winter run of Chinook salmon in the Sacramento River is listed as “endangered” under the federal Endangered Species Act. The Central Valley spring run is listed as “threatened.” The watershed also provides water to the regional municipal and industrial sectors. Primary stressors of concern include land-use change, population growth, and climate change.

Table 1. Comparison of the three watersheds

	Maryland	**San Pedro**	**Sacramento**
Size	Subwatershed scale (13−28 mi^2)	Watershed scale (~2,500 mi^2)	Basin scale (42,000 mi^2 SF Bay watershed)
Flow	Variance in daily streamflow has changed dramatically over the past 50 years; enhanced peak flows, and reduced baseflows are attributed to increased urbanization.	A portion of the flow in the San Pedro River comes from the groundwater aquifer, but there is large seasonal run-off resulting from heavy precipitation events during the "monsoon" season (July−August).	Flow maxima typically occur during the late winter through spring period and flow minima (dramatically reduced relative to peak flows) in the late summer and early autumn.
Ecosystem services (and assessment endpoints)	Habitat suitability for fish (temperature, siltation, flashiness, riparian zone condition, riffle vs. pool habitat)	Avian habitat suitability	Services related to water supply (quantity of flow and seasonality) for irrigated agriculture and fish habitat
Major stressors (other than climate change and land-use change)	Changes in water temperature, siltation rates, streamflow, riparian zone condition, and stress on aquatic habitats due to urbanization.	Groundwater withdrawals for agricultural and municipal uses; increasing water demand due to population growth.	Instream water withdrawals for urban populations, agriculture, and industry.
Modeling approach	System of submodels on climate, hydrology, ecosystem, land-use economics, and geomorphology.	System of submodels of climate, hydrology, ecosystem, groundwater flow, and geomorphology.	Linked climate, hydrologic model with information on water for fish habitat and irrigation.

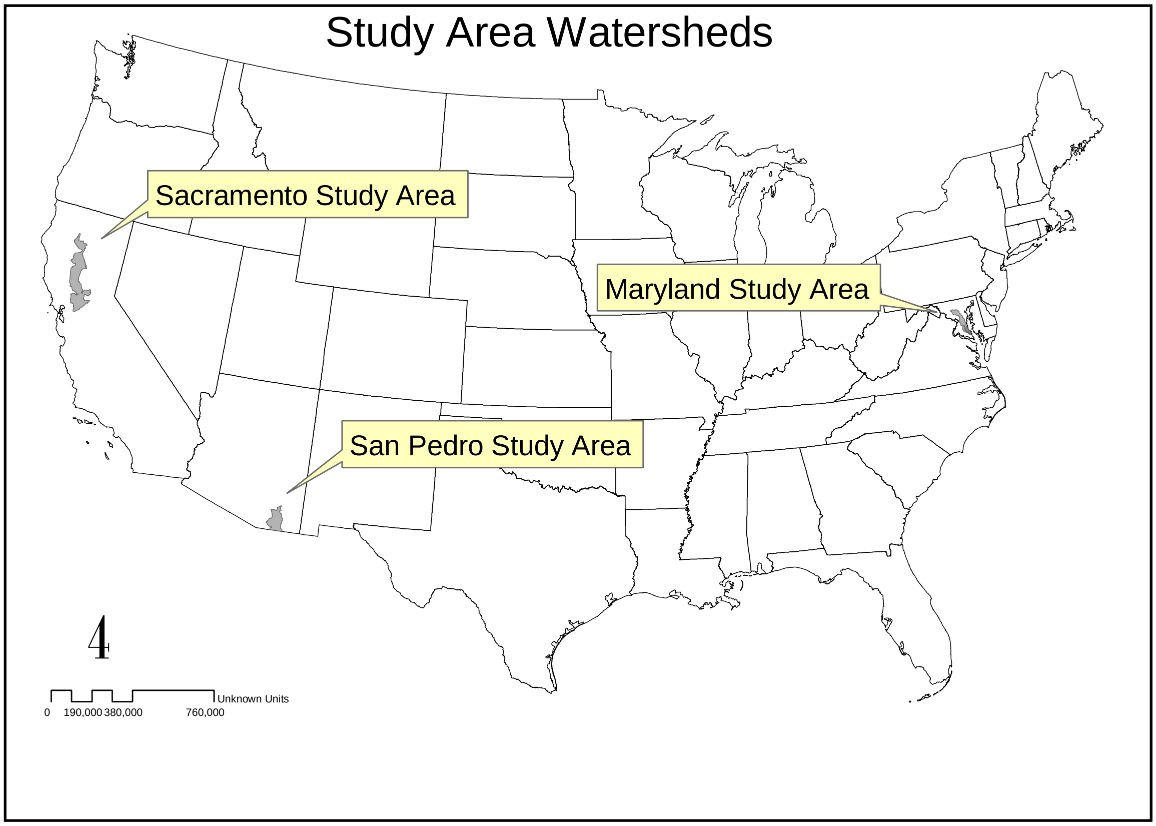

Figure 1. Geographic locations of case studies across the United States.

The studies' fundamental approaches were similar; all three case studies linked climate, hydrology, and ecosystem models. At their core, the analytic frameworks of all three studies were driven by integrated modeling systems that start by simulating the effect of climate change on hydrologic characteristics, and, subsequently, address how changes in these characteristics affect ecosystem functioning. Two of the three case studies, Sacramento and Maryland, also used results of large-scale climate models—known as General Circulation Models (GCMs)—to provide the bounds for, or to drive, the regional climate-change scenarios. The San Pedro case study relied on historical data rather than downscaled GCM results because the historical data provided more information on natural climate variability related to periodic regional-scale events. In the Sacramento and Maryland case studies, GCM outputs provided the basis for creating downscaled scenarios of temperature, precipitation, and derivative climate parameters. The San Pedro case-study team developed climate scenarios that represented a reasonable set of potential climate trajectories, given natural climate variability and the range of climate change projections for the region derived from climate models (SWRAG, 2000). They used a 52-year daily time series of historic weather data (1951−2002) to create transient climate scenarios for the period 2003−2102. All case studies used multiple climate scenarios rather than limiting their investigation to one particular future projection. This attempt to bound the range of plausible futures was used in recognition of the documented uncertainties inherent in simulating future climate.

The three case studies all examined climate change along with population and other land-use-related stressors, but the choices of specific stressors were different. For example, the Sacramento study included in-stream water withdrawals; the San Pedro case study carefully examined groundwater withdrawals; and the Maryland study focused on sediment load due to land-use change. Because of the differences in focus, there were also differences in model components. In the Sacramento River Watershed, model components were added to simulate groundwater flow and geomorphology. The San Pedro case-study team developed a model to simulate the effects of flow changes on riparian vegetation. The Maryland case-study team used geomorphologic models to simulate changes in sediment load and bed sediment composition.

The relative effects of climate change, land-use change, and other stressors demonstrated by each of the case-study teams showed a mixed response, with each of the systems exhibiting different sensitivities based on the region, the current stressors, the management goals, and the anticipated changes.

2. CASE-STUDY RESULTS

The following section discusses the three case studies, including background on each of the regions, goals of the project, major stressors, assessment methods, results, adaptation options (if analyzed), and how the case studies are applicable to other regions.

2.1. MARYLAND

The team for this case-study assessed the potential combined effects of land-use and climate variability and change on the composition of the fish assemblages of first- through third-order headwater streams in four watersheds of the greater Washington, DC metropolitan area. The watersheds lie primarily within the Piedmont physiographic province, and range in size from 13−28 mi^2—much smaller than the watersheds addressed by the other case studies. These sites were selected because they have all experienced major changes in land use—but with differing patterns.

Figure 2 shows the study site locations in the accompanying map (from Nelson et al., 2009). Three of the four watersheds are in Montgomery County (Hawling River, Northwest Branch, and Paint Branch). One of them, Cattail Creek, is in Howard County, which has different growth and planning policies. All four watersheds have similar amounts of remaining forested land; however, the Northwest and Paint Branches have more residential development, whereas Hawling and Cattail have more agricultural land. Most of the urban development in these watersheds occurred since World War II, with additional development episodes in the late 1960s and early 1970s.

2.1.1. Goals of the Case-Study Assessment

The project’s goal was to better understand how the effects of climate variability and change on stream ecosystems depend on land-use choices in surrounding areas. This understanding is intended to provide decision makers with information about the ecological consequences of alternative land-use configurations that will assist them in developing potential strategies for adapting to climate change and variability.

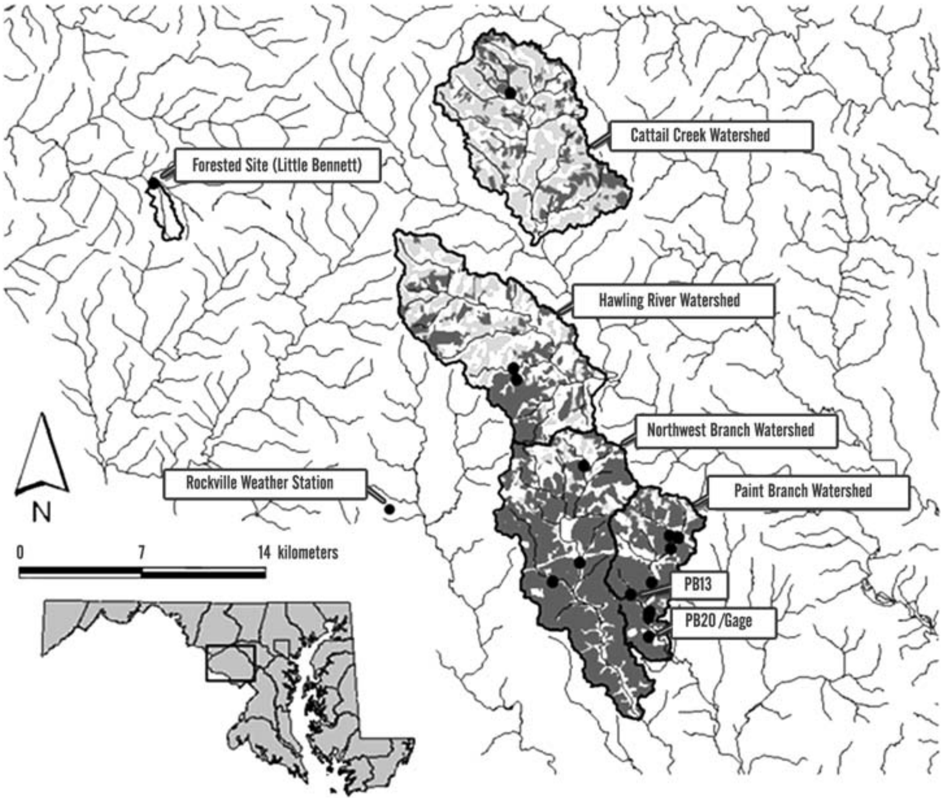

Figure 2. Study site locations (watersheds outlined with specific sites indicated by black dots), gauging site, and weather station. Within the watershed boundaries, dark grey represents urban land, light grey represents agricultural land, and white represents forested land.

2.1.2. Major Stressors

Climate change, land-use change, and land cover change, specifically urbanization, increases in impervious surface, and destruction of streamside vegetation are associated with stream degradation at the Maryland case-study sites. Streams, which occupy topographic lows, collect runoff and sediment discharge, making them highly vulnerable to land-use and climate change. Urbanization, in particular, is a major stressor on habitats in Maryland, contributing to changes in aquatic temperature, siltation rates, streamflow, riparian zone condition, and the availability of riffle versus pool-type habitats for fish (Nelson et al., 2009; Nelson and Palmer, 2007).

Climate change is projected to cause a 2−11.5°F warming nationally by 2100 (Karl et al. 2009), but the consequences of this warming depend on the seasonality of temperature shifts. For example, fewer—but more intense—storms in summer could produce storm-related heating in much the same way that urbanization does. Storm-related heating results from heavy rains that increase runoff over impervious surfaces, leading to spikes in stream temperatures (Nelson and Palmer, 2007).

The specific stressors that were modeled in the Maryland case study were air temperature and precipitation from downscaled GCMs and land-use variables (extent of impervious cover, percentage forested land, percentage of new construction).

2.1.3. Assessment Methods

The endpoint of interest for this watershed study was the suitability of a stream environment for selected fish species. Fish assemblage composition was chosen by the Maryland case-study team as the assessment endpoint because fish are effective indicators of systemic stressors and are widely used as indicators of environmental quality (Fausch et al., 1990; Karr, 1981).

To understand how changes climate and urbanization, separately and in combination, affect fish assemblages, the Maryland case-study team integrated five submodels. These models included downscaled climate projections (daily air temperature and precipitation), hydrology, geomorphology, water temperature, and fish growth and reproduction. Each of the submodels is outlined below, followed by a description of the land-use scenarios used for the case study; additional details are provided in Nelson et al. (2009).

2.1.3.1. *Submodels*

2.1.3.1.1. Downscaled climate projections

Projections of air temperature and precipitation over the period of 2085−2094 were from the U.S. Department of Energy/National Center for Atmospheric Research Parallel Climate Model (PCM; Washington et al., 2000) and the U.K. Meteorological Office Hadley Centre Model v3 (HadCM3; Gordon et al., 2000; Pope et al., 2000). These coupled atmosphere-ocean GCMs were run under two sets of future emissions scenarios developed by the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakićenović et al., 2000)—the A2 (medium-high within the full range of scenarios) and B2 (medium-low within the full range of scenarios) (see Table 2). The outputs from these climate realizations were statistically downscaled for the specific location of Rockville, MD. Climate sensitivity is a metric that captures the magnitude of the model-simulated increase in global temperature in response to a doubling of atmospheric CO_2 concentration. Present climate is taken from the years 1995−2004 based on historical simulations by the HadCM3 model and statistically downscaled to match observed historical distributions.

Table 2. **Comparison of Maryland baseline and climate change scenarios.** Climate change driver series used in the Forecasted Indices for Fish (FIF) for baseline and future climate scenarios.

Statistic	Baseline	Hadley A2	Hadley B2	PCM A2	PCM B2
Mean annual air temperature (Mar−Sept)	17.2ºC	20.5ºC	21.7ºC	15.5ºC	**15.3ºC**
No. of rainfall events in 10 years (>0.1 cm)	1,170	1,087	1,093	1,104	**1,047**
Average annual *P*	112.9 cm	132.9 cm	111.9 cm	116.9 cm	**94.1 cm**
Average *P* event^{-1}	1.02 cm	1.22 cm	1.10 cm	1.05 cm	**0.90 cm**
No. of heavy *P* events year^{-1} (>10 cm)	5	13	10	3	**0**
Max 1-Day *P*	17.4 cm	21.1 cm	26.7 cm	10.3 cm	**8.4 cm**
Summary compared to present:					
Average summer *T*		Warmer	Warmer		
Total *P*		Wetter			**Drier**
Heavy *P* events		**Increased**	**Increased**	**Decreased**	**Decreased**

Source: Nelson et al. (2009).

2.1.3.1.2. Hydrology

The hydrology submodel is a continuous streamflow model that projects daily streamflow over the course of a scenario to capture flashiness. Three different forms of runoff were examined: surface runoff, subsurface runoff, and groundwater runoff. The model requires inputs of daily precipitation and temperature, along with variables giving land-use characteristics and geology (Nelson et al., 2009).

2.1.3.1.3. Geomorphology

The geomorphology submodel, a sediment transport model, computes changes to the stream bed as a function of climate and land-use changes. Output is on a daily time-step and includes particle size distribution, bedload and suspended material discharge, turbidity, and interstitial clogging (Nelson et al., 2009). The land-use variables that drive the hydrologic and geomorphic submodels are discussed below.

2.1.3.1.4. Water temperature

The water temperature submodel uses the methods of Mohseni et al. (1998) to project minimum and maximum instream temperatures based on a daily air temperature series derived from the downscaled climate projections, percentage deforestation, and watershed size.

2.1.3.1.5. Forecasted Indices for Fish (FIF)

To model food availability, FIF uses a data series giving daily estimates over the course of the year of detritus, algae, small invertebrates, and small fishes as food sources. This approach was taken because there are no calibrated models that predict fish food availability as a function of flow, temperature, and geomorphic conditions. The data series was developed using literature values, data from the study sites, and expert opinion. Details are provided in Appendix S2 of Nelson et al. (2009).

Changes to the baseline values for food resources are driven by changes in temperature and flow. The model assumes that flashier flow will reduce the abundance of invertebrates and their foods, and that high summer temperature combined with low summer flow will increase this effect (Nelson et al., 2009).

Fish spawning and growth vary as a function of temperature and flow (direct effects) as well as food availability (indirect effect). The spawning and growth results over any 10-day period are combined into indices, which are then related to a matrix of fish traits to predict vulnerable species and the composition of the fish assemblage under a given scenario. The indices were validated using an independent data set on fish assemblages across urbanization gradients. Additional details on the FIF and its various components are given in the supplementary online material provided by Nelson et al. (2009).

In turn, outputs of these submodels determine instream habitat conditions. Instream habitat, along with estimates of food availability, control fish growth and spawning success. In the final modeling step, the fish submodel calculates indices of spawning days available, spawning substrate, juvenile growth, and adult growth. These indices are then related to a matrix of fish traits to determine which species are most vulnerable under a given scenario and the resulting composition of the fish assemblage (Nelson et al., 2009).

2.1.3.2. *Land-Use and Climate Change Scenarios*

To simulate potential land-use change, three variables were used: percentage impervious surface, percentage new construction, and percentage of watershed forested. These variables influence infiltration capacity, sediment input, and water temperature and organic input. Agricultural land use was not included in the scenarios because little of the remaining land surrounding Washington, DC is dedicated to agricultural use, and there is little difference in the hydrologic outputs for agricultural versus residential land use.

The case-study team examined two scenarios of land-use change along with the four climate change scenarios. The baseline land-use scenario assumed 10% impervious surface, 20% forested, intact riparian buffers, and no on-going construction in the watershed. The urbanization scenario assumed 30% impervious surface, 2% forested, no intact riparian buffers, and 2% of the watershed under construction (see Table 3 for details of each of the scenarios). The baseline scenario represented actual conditions in the study area. In total, 10 scenarios were examined—1 baseline scenario with present climate and present day urbanization (“Baseline”), 4 climate change scenarios with present day urbanization (“Climate change only”), 1 scenario with increased urbanization and no climate change (“Urbanization only”), and 4 climate change scenarios with increased urbanization (“Urbanization + climate change”).

2.1.4. Impacts and Findings

Under two scenarios (Hadley A2 and B2), March through September temperatures were higher than baseline temperatures by 3.2−4.5°C and lower under other scenarios (PCM A2 and

Table 3. Summary of Maryland's 10 land-use and climate change scenarios used to project impacts on stream fish assemblages

Scenario	**Percentage impervious**	**Percentage forested**	**Presence of riparian buffer**	**Percentage watershed under construction**	**Climate**
Baseline	10	20	Yes	0	**Present**
Climate change only	10	20	Yes	0	**Future**
Urbanization only	30	2	No	2	**Present**
Urbanization + climate change	**30**	**2**	**No**	**2**	**Future**

Source: Nelson et al. (2009).

B2) by 1.7−1.9°C." Total precipitation showed the same pattern of increases over baseline for the Hadley A2 and B2 and decreased from baseline for PCM A2 and B2. The projected precipitation trends were more significant than future temperature trends in their influence on hydrological and ecological processes (Nelson et al., 2009). HadCM3 scenarios projected more extreme temperature changes and a doubling of scouring extreme precipitation events. The PCM-based climate change scenarios had relatively little changes in precipitation, less scouring extreme precipitation events, and minimal changes in temperature.

Using these projected changes in temperature and precipitation, the FIF projected results for each of the following indices for each species: spawning day availability; spawning substrate; juvenile growth; washout on eggs and young-of-year; adult growth; feeding efficiency; and thermal maximum. The pathways that proved to have the greatest impact on fish species from increased urbanization and climate change were stresses on juvenile growth (from altered temperature and hydrology), and stresses on adult growth (from altered changes in temperature, siltation, and food resources). For the nine scenarios that projected changes in urbanization and/or climate change, species adversely affected through reductions in juvenile or adult growth numbered between 8 and 29 of the 39 fish species studied. Urbanization alone affected few species, primarily by reducing adult growth (8 of 39 species). However, climate change alone affected the most species (22−29 of 39 species, depending on the scenario). Urbanization and climate change together typically increased the number of stressed species through depression of adult growth (2−14 species, depending on the scenario). Pathways for such results are increased siltation in the PCM-based climate scenarios and increased flashiness in the HadCM3 scenarios. Of those species projected to be affected, urbanization and climate change significantly affect almost all of the recreationally important species, including trout, bass, and sunfish. Overall, these results suggest that community composition could change significantly with climate change and/or increased urbanization, causing a loss of diversity under future projected changes (Nelson et al., 2009).

2.1.5. Methods and Results Applicable to Other Watersheds

The downscaled climate projections used in the Maryland case study could be used for other studies in the region. The hydrology, geomorphology, and water temperature models are transferable to regions where similar processes are dominant, as long as the modeled empirical relationships are the same and it is possible to reparameterize the models with local data (e.g., North Carolina Piedmont). The FIF could be applied to other Piedmont streams and other watersheds of the U.S. East Coast with a similar species mix. The fish assemblage of the Maryland Piedmont is more likely to apply to a similar region such as the North Carolina Piedmont rather than the Maryland coastal plain, even though the latter is geographically closer. For streams with different fish assemblages, it may be possible to develop a similar model if local data are available on food resources and on the recruitment, growth, and survival of the species of interest.

2.2. SAN PEDRO

The Upper San Pedro River riparian ecosystem in southeastern Arizona and northern Sonora, Mexico (shown in Figure 3) is of critical importance in maintaining regional biodiversity at the ecotone between the Sonoran and Chihuahuan deserts and the plains grassland. It contains one of the richest assemblages of species and supports one of the most important migratory bird habitats in western North America. The biodiversity found along the Upper San Pedro River exceeds that found almost anywhere else in the United States due, in part, to the fact that in other regions, many natural habitats have been lost. More than 20 different biotic communities occur in the basin, and the river sustains three vegetation types that are considered “threatened”:

Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) forests; river marshlands (cienegas); and big sacaton (*Sporobolus wrightii*) grasslands (Price et al., 2005).

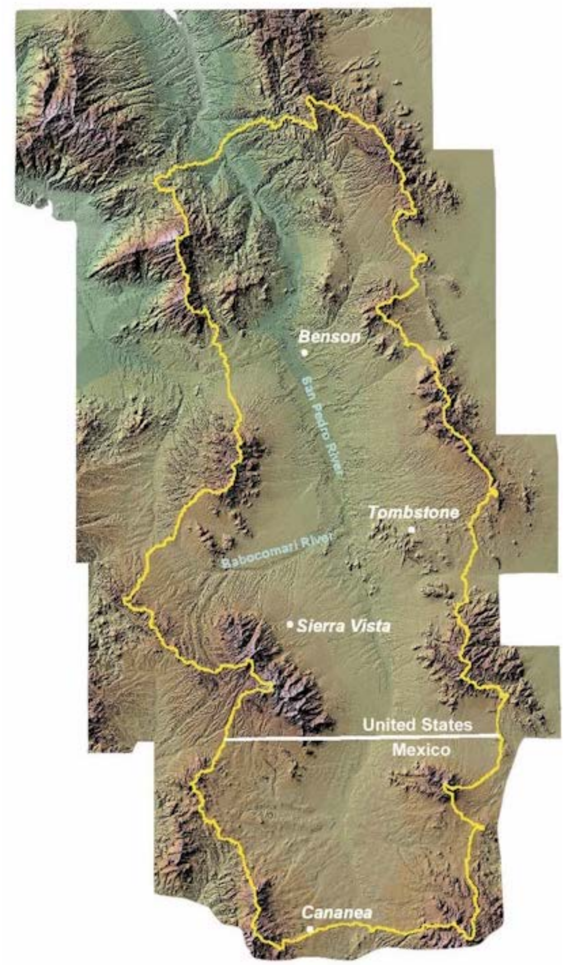

Figure 3: Map of the Upper San Pedro River riparian ecosystem.

The abundance, diversity, and health of riparian vegetation and wildlife in the Upper San Pedro are strongly influenced by river geomorphology and the hydrologic regime, including the amount, timing, and pattern of surface and groundwater flows. Channel and river flow conditions have changed dramatically over time, with accompanying changes in riparian vegetation. Prior to 1850 (approximate), the San Pedro was shallower, with marshes—with longer stretches of perennial flow than are observed today—and a mosaic of vegetation, including cienegas, sacaton grasslands, and more patches of riparian woodlands of cottonwood, willow, and ash (Arias Rojo et al., 1999). From 1850 to the mid-19th century, there was a period of channel down-cutting (incision), followed by entrenchment, and the formation of a wide, braided channel resulting from factors such as reduced soil infiltration due to overgrazing and large floods. Subsequent declines in floodplain groundwater and high fluvial disturbance in the widened channel destroyed most of the existing riparian vegetation and the floodplain. After the 1950s, there was a decline in flood magnitudes and rates of fluvial disturbance, allowing vegetation colonization, channel narrowing, and formation of a new floodplain. Today, the Upper San Pedro is characterized by cottonwood-willow forest. Increases in recruitment of these species have been linked to an increase in the size and frequency of winter floods since about 1960. However, increased channel narrowing in recent years is now reducing the availability of open substrate for colonization (Price et al., 2005 and references therein). It should be noted that the San Pedro is also distinguished from other rivers in the region because it is one of the few that remains undammed and it is partially ephemeral.

2.2.1. Goals of the Case-Study Assessment

The primary goal of the San Pedro case study was to model the likely effects of climate change, coupled with existing stressors, on riparian plant communities and associated avian species in the San Pedro Riparian National Conservation Area (SPRNCA; Price et al., 2005).

2.2.2. Major Stressors

Major stressors affecting the riparian ecosystem of the Upper San Pedro include groundwater pumping, land use, and, in the past decade, fire. Climate change, through direct effects on temperature and precipitation and indirect effects on water tables and evapotranspiration rates, is also increasingly important (Price et al., 2005).

River flow in the San Pedro results from a dynamic interaction between surface and groundwater flows. As a result of climate variability, surface water flow varies considerably both between and within years. During periods of low precipitation, the flow in the river comes primarily from groundwater inflow. During periods of storm flows, the shallow alluvial aquifer is recharged by the stream. Both low flows (base flows) and high flows (flood flows) are important for vegetation dynamics. The composition of the riparian vegetation community changes as the depth of the water table changes because of species differences in depth to rooting, drought tolerance, and saturation tolerance. Willow and cottonwood—and particularly the seedlings of these species—require the shallowest groundwater levels (Stromberg, 1998; Stromberg et al., 1996).

Because of the importance of groundwater for surface flows and riparian vegetation dynamics, groundwater pumping is an ongoing concern. Most of the pumped groundwater goes to agricultural use. According to the Arizona Department of Water Resources (ADWR), agriculture accounts for approximately 7,500 acre-feet of groundwater extraction annually, while other end uses, such as residential, industrial, and municipal, consume over 20,000 acre-feet of groundwater (ADWR, 2005). Although some of the pumped water returns to the aquifer via percolation, 70% of the water used for agriculture is lost. The primary crops in the area are alfalfa and pasture, which have low water return rates per unit of water used (ADWR, 2005). Over the next few decades, agricultural water use in the area is expected to decrease, while urban water uses are expected to rise (Price et al., 2005).

2.2.3. Assessment Methods

A simulation approach was used to evaluate the potential effects of groundwater depletion and climate change on riparian vegetation structure and dynamics at three sites along the Upper San Pedro River. Processes modeled included changes in the main vegetation communities (including riparian, mesic, and xeric), river baseflow, soil water content, channel migration, and the incidence and intensity of wildfires. Climate change scenarios were constructed from historical data, and vegetation dynamics were simulated as a function of the climate drivers and outputs from models of the primary physical processes influencing vegetation change, including streamflow, channel dynamics, and fire (Price et al., 2005).

The methods used to develop and implement each of these components of the analytical system are described below.

2.2.3.1. *Climate Change Scenarios*

Temperature and precipitation interact to influence the relative success of different vegetation types. For example, in the Upper San Pedro, a greater proportion of precipitation in summer may benefit perennial grasses, which have shallow roots and are intensive water users, and, therefore, benefit from more frequent rainfall during the summer growing season. Species with deep root systems, such as mesquite, may be favored when there is more precipitation in winter, which allows for deeper water infiltration by the start of the growing season. A combination of high temperatures and low precipitation may lead to high evapotranspiration rates and water stress for shallow-rooted, intensive water users like grasses. Increases in winter precipitation would increase recharge, while increased winter and summer temperatures would reduce recharge and increase evapotranspiration (Price et al., 2005).

To examine these dynamics in a changing climate, the San Pedro case-study team constructed five precipitation and temperature scenarios for the 100-year period from 2003 through 2102 using a 52-year time series of daily temperature and precipitation from the National Weather Service station in Tombstone, Arizona. Changes in precipitation and temperature were linearly applied to the historic data, which were used to preserve the periodicity of El Niño Southern Oscillation and Pacific Decadal Oscillation events. The scenarios were designed to correspond loosely to those reported for the southwestern United States over this century (SWRAG, 2000). Climate change projections suggest an increase in mean seasonal temperatures of 2−7°C over the next 100 years. While all GCMs broadly agree with this temperature increase, they differ in their projections for precipitation, and so the researchers examined both increases and decreases in precipitation (Price et al., 2005).

The five scenarios that were modeled include (Price et al., 2005):

- **Baseline (historical):** no climate change; daily temperature and precipitation data were generated by repeating the actual 1951−2002 data over the 100-year period 2003−2102.
- **Warm:** progressive temperature warming over 100 years, with a 4°C increase in maximum daily temperature and a 6°C increase in minimum daily temperature by 2102.
- **Warm and dry:** same progressive temperature warming as the warm scenario and a progressive decline in winter (nonmonsoonal: October 1−May 31) daily precipitation of 50% by 2102.
- **Warm and wet**: same progressive temperature warming as the warm scenario with a progressive increase in winter daily precipitation of 50% by 2102.
- **Warm and very wet:** same progressive temperature warming as the warm scenario with a progressive increase in winter daily precipitation of 100% by 2102.

2.2.3.2. *Simulation of Riparian Vegetation Dynamics*

Using a 5-day time step, changes in riparian vegetation were simulated as functions of changes in streamflow, channel migration, and wildfire in response to the different climate change scenarios. Vegetation population dynamics (changes in recruitment, growth, and survival) were modeled at the scale of individual sampling plots (10 m by 10 m) for three sites representing the range of physical conditions and vegetation composition along the Upper San Pedro River. All plots began with a 20% cover of both annuals and wetland plants (Price et al., 2005).

Models of the major geophysical processes (stream flow, channel migration, and fire) that drive riparian vegetation dynamics along the Upper San Pedro are outlined below, followed by a description of the vegetation model itself. The output of the geophysical process models are the key inputs to the vegetation model. Additional details on the models are given in Price et al. (2005).

2.2.3.2.1. Streamflow

Daily streamflow was modeled using the Soil Water Assessment Tool (SWAT), a physically based hydrologic model designed to project the effects of land management practices on water and sediment yield in complex watersheds over long time periods (Srinivasan et al., 1998). In addition to daily temperature and precipitation, input data for SWAT include soils, topography, vegetation, land management practices, and parameters representing streamflow-groundwater interactions. SWAT outputs of daily streamflow were inputs to MEANDER, the model of channel migration described in the next section.

2.2.3.2.2. Channel migration

The MEANDER model (Odgaard, 1989) used daily streamflow outputs from SWAT to project lateral channel migration under the different climate change scenarios. MEANDER models channel migration as a function of channel hydraulics, annual stream power, and spatial heterogeneity in bank erodibility. Channel migration in the model was calibrated using aerial photographs of channel locations in 1973 and 1996 and annual cumulative stream power from daily flows over the period 1973−1996 taken from nearby U.S. Geological Survey stream flow gages (Price et al., 2005).

2.2.3.2.3. Fire

To examine the effects of fire on riparian vegetation dynamics, the San Pedro case-study team modeled fine fuel moisture, probabilities of fire occurrence, and fire intensity as a function of relative humidity, temperature, wind speed, and precipitation. Fire has become more frequent along the Upper San Pedro in the past decade, possibly as a result of fuel build-up from removal of cattle and an increase in winter storms during El Niño years. Because riparian plant species vary in their rates of resprouting following fire, the intensity and frequency of fire may have important effects on riparian patch dynamics. In general, saltcedar, willow, velvet ash, and mesquite show higher resprouting under low-to-moderate intensity fires compared to cottonwoods. More frequent fires could reduce all trees and shrubs and shift the balance to grasses. In fact, there is some evidence for higher proportions of grassland compared to riparian forest and woodland on sites where fire has occurred in the last 10 years (Price et al., 2005).

2.2.3.2.4. Vegetation model

The vegetation model was developed using the STELLA II Dynamic Simulation Software (Peterson and Richmond, 1996). The model simulates effects of changes in climate (precipitation and temperature), streamflow, channel dynamics, and fire on the recruitment, growth, and mortality of the following 10 species and functional groups of southwestern riparian plants: Fremont cottonwood; Goodding’s willow; riverine marsh (cienega); mesquite woodland; saltcedar shrublands; a hydromesic shrub group; a xeric riparian shrub group; herbaceous annuals; wetland perennials; and mesic perennial grasses. Climate inputs included incident solar radiation, air temperature, precipitation, relative humidity, and wind speed, averaged (or summed) over each 5-day time step of the model. Solar radiation and mean daily temperature were used to calculate potential evapotranspiration using the Jensen-Haise (Wright and Hanson, 1990) and Hargreaves (Wu, 1997) methods. Soil and plant moisture dynamics were modeled as a function of precipitation, plant cover and moisture uptake, and potential evapotranspiration. Plant growth was modeled as a function of light availability (modified by leaf area above the plant), crowding, air temperature, moisture availability (soil water and groundwater), disturbance, and plant life history characteristics (Price et al., 2005).

2.2.3.3. *Changes in Avian Biodiversity Resulting from Vegetation Changes*

Expert judgment about likely changes in avian biodiversity in response to predicted vegetation changes focused on 87 abundant bird species in the SPRNCA. The expert used the relative degree of species' dependences on (1) dominance by riparian species in the vegetative community; (2) extensive and nonfragmented stands of riparian forest; (3) wetland habitat; and (4) running or standing water to predict future avian community composition (Price et al., 2005).

In addition to this analysis, likely changes in the relative abundances of five rare bird species were evaluated using Habitat Suitability Index (HSI) models developed by a biologist on the project team. The five species were Botteri's sparrow (*Aimophila botterii arizonae*), southwestern willow flycatcher (*Empidonax traillii extimus*), Wilson's warbler (*Wilsonia pusilla*), yellow-billed cuckoo (*Coccyzus americanus occidentalis*), and yellow warbler (*Dendroica petechia*). The southwestern willow flycatcher is an "endangered" species, and several groups have petitioned the U.S. Fish and Wildlife Service (USFWS) to list the yellow-billed cuckoo as "threatened" or "endangered" (USFWS, 1981).

HSI models were introduced in the 1970s by the USFWS. HSI models are developed from available information on the habitat preferences and patterns of habitat use of the species of interest. The models are considered hypotheses of species-habitat relationships rather than statements of proven cause-and-effect relationships. The value of these hypothesis-based models is that, because they can be tested and improved as needed, they lead to increased understanding of habitat relationships for management purposes. Once the models are verified with field observations, they can be used to evaluate the likely effects of an actual or potential change in habitat quality on a habitat's "carrying capacity," i.e., the habitat's capacity to support a species (USFWS, 1981).

HSI models are developed by the following:

- Identifying the critical habitat variables that affect the habitat's carrying capacity for the species of interest.
- Establishing relationships between the occurrence of these variables and the carrying capacity of the habitat. Each variable is assigned a suitability index (SI). This is a score between 0 and 1, where the former is completely unsuitable habitat (i.e., minimal carrying capacity) and the latter is optimal habitat (i.e., greatest carrying capacity).

- Developing metrics that can be used in the field to quantify the occurrence of the critical habitat components (and, therefore, the carrying capacity of the habitat).
- Developing algorithms that combine the variable scores (SIs) into an expression of the overall carrying capacity of the habitat. This final score is the HSI and can be between 0 (unsuitable for species or guild) and 1 (optimal habitat).

In the San Pedro case study, HSI models were developed by the project team for Botteri's sparrow, southwestern willow flycatcher, Wilson's warbler, yellow-billed cuckoo, and yellow warbler and used to make expert judgments about the likely impacts of predicted vegetation changes on the habitat's capacity to support these species (Price et al., 2005).

2.2.4. Impacts and Findings

Vegetation modeling indicated that changing hydrology and climate change may fundamentally impact vegetation in the SPRNCA by fragmenting existing riparian and wetland communities and leading to their replacement by more mesic or xeric communities (i.e., vegetation more typical of the desert matrix). The influence of climate change on pioneer riparian communities will depend on the magnitude and direction of precipitation changes. A decrease in winter precipitation will likely result in fewer winter floods, lower rates of channel migration, and much lower cottonwood and willow recruitment rates. An increase in winter precipitation is expected to result in larger and more frequent winter floods, higher channel migration rates, and higher cottonwood and willow recruitment rates. Model results suggested a decreasing trend in coverage by pioneer woody vegetation across the floodplains of the Upper San Pedro over the next 100 years. At the same time, results indicated that coverage by later successional communities such as mesquite, ash patch types, and sacaton grassland are likely to increase over the next 100 years (Price et al., 2005).

The avian biodiversity modeling projected that 26% of the most abundant bird species would likely be vulnerable to, and adversely affected by, changes in the vegetative community due to climate change. An additional 25% could be relatively unaffected, and 43% could benefit. Results of the HSI models indicated that the species most dependent on the cottonwood/willow gallery forest would show the greatest projected decreases. Even without factoring climate change into future conditions, marked changes in habitat quality are projected for two of the five species. This change is caused by a maturation and contraction of the cottonwood/willow forest in the middle of this century; the change will result in decreased habitat for the yellow-billed cuckoo and an increase in habitat for the Botteri's sparrow as the forest is replaced with grassland and shrublands (Price et al., 2005).

The no change, warmer, and warmer drier climate modeling scenarios all resulted in a loss of riparian forest and wetlands and their replacement by mesic or xeric vegetation communities. High avian biodiversity in the SPRNCA is supported by the proximity of riparian gallery forest and wetland habitats within a matrix of desert scrub and grassland (Price et al., 2005). Loss of either of the habitats could reduce the biodiversity of the SPRNCA, because the birds that currently inhabit these areas are expected to be replaced by current occupiers of the desert scrub matrix. These findings suggest that climate change could have important implications for the ecosystem services provided by the SPRNCA (Price et al., 2005).

A decline in ecosystem services that sustain ecotourism could adversely impact demand for those activities within the region. The SPRNCA is a major attraction to wildlife viewers and ecotourists. If the gallery forest were to be fragmented or entirely lost as is projected under the three driest climate change scenarios, the area would be less attractive to the public. If future climate changes more closely resemble the warmer and wetter scenario, adequate water supply to the ecosystem might help maintain ecosystem services (Price et al., 2005).

Case-study findings indicate that a warmer wetter future climate does not pose as significant a threat for vegetation as a warmer drier climate projection. The case study did not separately quantify the effects of aquifer depletion and climate change. Climate change will cause changes in the ecosystem and aquifer even without water extraction and other forms of human interaction. The impact of aquifer depletion, however, is expected to be more dramatic in terms of scale than the effect of climate change alone on the San Pedro River ecosystem. Together, these two stressors will have a major combined effect (Price et al., 2005).

2.2.5. Methods and Results Applicable to Other Watersheds

The results from this case study and, in particular, the challenges of aquifer depletion are applicable to other areas. The vegetation, hydrology, and wildlife data inputs used in the models make them specific to the southwestern United States and other arid environments with groundwater-dependent riparian systems. Migration is useful in other regions, as long as the specific vegetation data are adapted. However, the approach is not applicable to systems where vegetation uses water from the unsaturated zone (Price et al., 2005).

2.3. SACRAMENTO

2.3.1. Goals of the Case-Study Assessment

The broad goal of this case study was to develop a model for assessing how global stressors may affect the balance of water supply and demand in the Sacramento River Watershed and the many ecosystem services in the basin that depend on freshwater. The case study focused on two services: offstream water supply for agriculture and instream flows for Chinook salmon.

2.3.2. Major Stressors

The Central Valley of California extends approximately 450 miles, from the headwaters of the San Joaquin River in the south to the headwaters of the Sacramento River in the north (see this area within the larger San Francisco Bay Delta Watershed in Figure 4). This area of approximately 42,000 mi^2 is referred to as the Sacramento River Watershed. The two rivers and their tributaries drain into the Sacramento-San Joaquin Delta (Delta), eventually flowing into San Francisco Bay and the Pacific Ocean. Water from the basin supports a number of highly valued ecosystem and human use services in the region, including agriculture, municipal and industrial uses, hydropower, recreation, and aquatic habitats and biota.

Historically, most precipitation occurred in winter (November−April), primarily as snow. Flow maxima occurred in spring from snowmelt runoff, while flow minima occurred in late summer. This general pattern prevails, but land use and water development—particularly the construction of large dams and reservoirs on all of the major rivers—have significantly altered the basin’s natural hydrology.

As the population has grown, agriculture and urban activities have required larger and larger quantities of the basin’s water. Irrigated land is currently stable or decreasing slightly, at about 1.5 million hectares, but the main crops continue to be those that are water-demanding (e.g., cotton, grapes, tomatoes, fruits, hay, and rice). In addition to uses within the basin, a significant amount of water is exported through Delta pumps to satisfy municipal and industrial demands along the Southern California Coastal Plain and agricultural demands in other basins

Figure 4: Map of the San Francisco Bay Delta Watershed, which includes the Sacramento River Watershed.

The rerouting and depletion of basin water supplies have resulted in several major changes to natural hydrology. Now winter peak flows occur earlier, and spring runoff is significantly reduced. Summer flows are higher than under natural conditions because of upstream reservoir releases to meet summer irrigation needs.

Projected climate changes will again change basin hydrology. It is anticipated that more precipitation in the basin in winter will fall as rain, reducing water storage in the snowpack, snowmelt runoff in spring, and summer base flows. At the same time, increased air temperatures will warm surface waters, potentially above the tolerances of the basin's aquatic life.

The model was designed to (1) understand the relationships among stressors and ecological processes and the aquatic ecosystem services they provide; (2) use this information, along with water resource models, climate change scenarios, and assumptions about the future intensities of existing stressors to project effects on the future functioning of these services; (3) provide stakeholders with information on how valued ecosystem services are likely to be affected, so that they can make informed decisions; (4) develop appropriate methodologies for assessing effects on ecosystem services that will be transferable to other large watersheds in different locations and settings; and (5) provide integrated decision support for issues of reservoir location, Federal Energy Regulatory Commission dam relicensing, and system operations to preserve the ecosystem services of interest or of regulatory necessity.

Agriculture is an important activity in the basin. Eight of California's 15 most agriculturally productive counties are in the Central Valley, which makes it one of the most important agricultural areas in the world. The main crops grown there—for example, cotton, grapes, tomatoes, fruits, hay, rice—are generally water-demanding. The annual crop value is typically in excess of $14 billion, and more than 30% of the total economy is attributed to agriculture. (California Research Bureau, 1997.)

Another highly valued ecosystem service provided by water in the basin is instream habitat for Chinook salmon. Chinook salmon populations have declined dramatically over the last century, primarily because of overfishing, the construction of dams that blocked access to historical spawning habitats, sedimentation of spawning beds, and water diversions that reduced flows and increased water temperatures during critical stages in the salmon life cycle (Yoshiyama et al., 1998).

Suitable spawning habitat for Chinook salmon in the Upper Sacramento River is currently dependent on releases of cool water from reservoir hypolimnia between May and September. Without these releases, the water temperatures would exceed the physiological tolerances of the eggs and juveniles of the winter and spring runs. Reservoir releases also keep summer water temperatures in the lower river at levels suitable for juveniles moving downstream. However, if releases of cool waters from upstream reservoirs between May and September are reduced or discontinued, summer water temperatures in the lower Sacramento River could reach levels that exceed the physiological tolerances of adult and juvenile salmon.

Climate change will exacerbate these problems. Water temperatures will show additional increases as air temperatures rise or precipitation and runoff decrease in response to global warming. It is possible that water temperatures could reach levels that will impair the ability of salmon to find any suitable cold water habitat.

The major stressors on water supply in the Sacramento River Watershed are population growth, land-use change, and, increasingly, climate change. Steady growth in population, particularly around existing urban areas and transportation corridors, directly affects the demand for water in the Sacramento River Basin. In addition, changing land use, in particular, the extension of urban area into other land-use types, stresses water supply and demand in the basin. Climate change is expected to exacerbate these demands on water (Yates et al., 2006).

The primary problem caused by land-use change and population growth in the Sacramento River Basin is the transfer of water from irrigated agricultural systems and into the urban environment (Yates et al., 2006). The scale of water development in California is among the most substantial in the world, with water often being shifted from one basin to another over distances of hundreds of kilometers to satisfy water demands. Much of the water in the basin is exported through pumps in the Delta in order to satisfy municipal and industrial demands along the Southern California Coastal Plain and agricultural water demands in other basins. Land-use change and water development—particularly the construction of major reservoirs on all of the major rivers—has altered surface water hydrology in the basin and created peak flow conditions earlier in the winter and reduced spring flows. In addition, summer flows are higher than under natural conditions because operators attempt to meet summer irrigation demands by releasing water downstream (Yates et al., 2006). Climate change—particularly projected increases in summer temperatures—is expected to cause an increase in water supply requirements for all land uses (Yates et al., 2006).

The two major challenges in water management under these conditions are (1) to overcome the spatial and temporal mismatch between where and when precipitation occurs and where and when water is needed, and (2) to balance offstream uses for agriculture and urban areas with instream needs for aquatic habitats and biota.

2.3.3. Assessment Methods

The case-study team applied the Water Evaluation and Planning (WEAP) modeling system to analyze tradeoffs among offstream and instream water needs. The model recognizes that water supply is defined by the amount of precipitation that falls on a watershed and is depleted through natural watershed processes, with evapotranspiration being the first significant point of depletion. The residual supply is available to the water management system. WEAP is thus able to link climate, land-use/land-cover conditions, and water management (Yates et al., 2006).

WEAP includes a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners using a scenario-based approach. The list of issues includes climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure. Biological requirements in the model, such as fish mortality or reproduction, can be related to projected climate characteristics as well as hydrological and water quality characteristics (Yates et al., 2006).

In the modeling process for this study, the Sacramento River Basin was divided into more than 100 subcatchments, groundwater basins, irrigated areas, and urban demand centers in an attempt to completely characterize the forces that act on water in the basin. A monthly climate time series from 1962−1998 was used to drive a distributed hydrologic model that simulates runoff, groundwater-surface water interactions, and consumptive water demands. Water management infrastructure, including reservoirs, canals, and diversions, was superimposed over the physical watershed. A verification analysis showed that the model is able to reproduce both local and regional water balances for the 37-year period, including managed and unmanaged streamflow, reservoir storage, agriculture and urban water demands, and the allocation of groundwater and surface water supplies (Yates et al., 2006).

This study evaluated the impact of four climate scenarios on water management in the region and whether water management adaptation could reduce the potential impacts of climate change on irrigated agriculture and salmon habitat. The four climate scenarios were derived by downscaling the output from two GCMs (Parallel Climate Model and Geophysical Fluid Dynamics Laboratory) and two emission scenarios (A2 and B1) to a 1/8-degree grid over California. The A2 and B1 emission scenarios are from the *Special Report on Emissions Scenarios* published by the Intergovernmental Panel on Climate Change (Nakićenović et al., 2000). The A2 storyline describes a heterogeneous world where local identities dominate, economic development is regionally oriented, and per capita economic growth and technology change are more fragmented and slower than in other storylines. The B1 storyline describes a world where economic growth is rapid and there is convergence among nations, capacity building, and increased cultural and social interactions. In the B1 storyline, there are rapid changes in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The four climate scenarios were (1) Parallel Climate Model with an A2 scenario; (2) Parallel Climate Model with a B1 scenario; (3) Geophysical Dynamics Laboratory with an A2 scenario; and (4) Geophysical Dynamics Laboratory with a B1 scenario (Yates et al., 2006).

Simulations also took cropping patterns and irrigation management into account. In one simulation, cropping patterns and irrigation management remained fixed over the course of a 100-year simulation. In a second simulation, cropping and irrigation management changed with climate. The case study did not isolate climate and land-use stresses to determine their individual effects on the system (Yates et al., 2006).

2.3.4. Impacts and Findings

Two of the four climate scenarios predicted a decreasing trend in precipitation over the next century, with the other two scenarios showing less pronounced changes—one scenario predicted slightly wetter conditions at the end of the century, and the other showed a decrease in precipitation in normal-dry years and an increase in precipitation in normal-wet years. All four scenarios predicted increases in average winter and summer temperatures over the next century ranging from a lower bound increase of 1.5°C in winter and 1.4°C in summer to the higher bound of 3.0°C in winter and 5.0°C in summer.

Key hydrologic factors were examined under the four scenarios to determine whether existing water management was capable of responding to potential climate and land-use changes. For the first hydrologic factor—annual inflows to reservoirs—two scenarios projected increased annual inflows to the major reservoirs and two projected lower annual inflows.

The second hydrologic factor was changes in the timing of stream flows. All scenarios showed earlier stream flows compared to historic conditions, which would have the greatest effect on those basins dependent on snow melt runoff (e.g., Sacramento watershed above Lake Shasta).

Persistence of drought conditions, the final hydrologic factor, was projected to be less severe than the historical record under two scenarios. A third scenario projected that droughts comparable in magnitude to the early 1990s drought would occur with regularity. The fourth scenario projected a very severe drought during the last 15 years of the century (Yates et al., 2006).

All four scenarios showed an increasing trend in water requirements with time. The increasing water supply requirements were due primarily to increasing summer temperatures and increasing crop water demands as summer temperatures increased.

Groundwater pumping was projected to be relatively stable for all scenarios for the period 1960−2064. In the last period, 2070−2099, pumping increased significantly in dry years for one scenario when surface water deliveries were less reliable. Aquifers in the region showed relatively stable fluctuations around a mean for most of the period between 1960 and 2070. During this period, the surface water deliveries were increasing as a result of growing crop water requirements, so that groundwater pumping levels were only marginally increased. During the final period of analysis (2070−2099), however, an extended 10-year drought in one scenario shifted agricultural water supplies to groundwater. As a result, groundwater levels decreased sharply (Yates et al., 2006).

Future climate changes, particularly shifts in temperature and precipitation patterns could lead to further reductions of the Chinook salmon’s fragmented habitat. Specifically, increased water temperatures were projected to result in exceedances of critical spawning and rearing temperatures, thus jeopardizing the productivity of Chinook salmon (Yates et al., 2006).

The Sacramento case-study team considered two adaptation approaches, one focused on cropping practices to reduce water demand, the other focused on water management to maintain suitable instream flows for salmon. The first was incorporated into the WEAP model and consisted of strategies to adapt cropping practices. The options analyzed included improved irrigation efficiency and changes in cropping patterns in response to water supply conditions. The results showed a decline in water supply requirements as improvements in irrigation efficiency were implemented (Yates et al., 2006).

Adaptation options for salmon focused on managed releases of cold water stored in reservoirs. The schedule and magnitude of releases can be used to ensure adequate instream flows. Ironically, more ‘natural’ and unmanaged systems may provide fewer opportunities for adaptation to climate change effects (Yates et al., 2006). Because Chinook salmon are coldwater fish, they may be particularly vulnerable to increasing water temperatures as a result of climate change. Rising water temperatures in their natal rivers could adversely affect the salmon’s ability to find suitable breeding habitats, especially because that habitat has already been reduced by dam construction. However, dams allow scheduled releases of cold water stored in reservoirs, such that the frequency and timing of these releases could be used to aid salmon survival during spawning (Yates et al., 2006).

2.3.5. Methods and Results Applicable to Other Watersheds

In most managed water systems, a major challenge is to balance the complex tradeoffs and interactions of the multiple uses of water (e.g., water for food and water for environment), some of which are in conflict, and others which are not. The WEAP model framework has proven useful for this purpose, with the flexibility to apply to multiple locations and systems. The intrinsic logic behind WEAP is universal and could be easily adapted for other locations using site-specific data.

Further, the results from this case study would apply to other watersheds that are similar in character and nature. For example, if agricultural sector water demand is scaled back due to improved irrigation efficiency and changes in cropping practices, there will be more water for other sectors. Given that all water resource systems and hydrologic systems are unique, however, the specific results would not be transferable. In other words, the results would be applicable qualitatively—but not quantitatively.

3. FINDINGS AND RECOMMENDATIONS

NCEA GCIA initiated a set of watershed case studies to gain a better understanding of the effects of global change on aquatic ecosystems and water quality, and to build capacity to respond to these effects at appropriate levels of decision making. The case studies demonstrated that certain factors help ensure a sufficient "capacity" for conducting assessments that produce useful information. The discussion and recommendations below are centered on (1) whether the assessment processes and results from the studies are useful in furthering our understanding of global change effects beyond the specific places in which the studies were done and the factors that would improve usefulness and transference in the future, and (2) the effectiveness of each case-study team's stakeholder and communication processes and the factors that would enhance these processes in the future (see Table 4 below for a list of the recommendations).

Table 4. Summary of recommendations for future watershed assessments

Assessment process	Stakeholder process
• Provide keystone capabilities and tools to project teams • Emphasize model linkages to ensure seamless integration • Carry out assessment activities at multiple scales • Require explicit uncertainty analyses in assessments	• Build on existing stakeholder relationships - Target selection - Establish credibility • Incorporate incentives for mutually beneficial results • Design selection criteria to maximize decision support

3.1. ASSESSMENT PROCESSES AND RESULTS

The first question is whether the assessment processes used by each case-study team are instructive to other project teams, and whether the climate impacts information generated is useful to specific decision makers and applicable to other geographic regions. The sections below discuss the composition of each case-study team and the methods used for facilitating effective scientific collaborations (see Section 3.1.1); the research design and ways in which specific results from each of the case studies may be more broadly useful (see Section 3.1.2); the methodological issues related to the spatial scale of each study and how to address these issues in the future (see Section 3.1.3); and each case-study team's treatment of uncertainty and methods for improving estimation and communication (see Section 3.1.4).

3.1.1. Case-study Team Composition and Management

3.1.1.1. *Findings*

Given the multidisciplinary nature of the assessments, and the complexity of the models, all three case-study teams included multiple investigators and disciplines. The San Pedro and Maryland case-study teams included experts in hydrology, geomorphology, and aquatic and avian ecosystems. The principal challenge in both of those case studies involved linking a series of separate models to provide an integrated analytical capability suitable for the assessment endpoints selected. Both San Pedro and Maryland invested considerable effort in developing new research approaches that involved modifying existing models and linking those models to provide a complete assessment capability that started with the physical effects of climate change and finished with some measures of ecological changes.

The Sacramento case-study team primarily chose hydrologic endpoints (i.e., flows and quantities of water), and, consequently, balanced their expertise in hydrology with some expertise in ecology. Rather than developing new models, they selected an existing modeling framework that integrates water supply, demand, and quality to address the complexity of the water management system in California (the WEAP model).

The Team Managers/Principal Investigators of all three case-study teams were faced with a challenging series of tasks, including:

- Guiding their teams through an extensive scoping and method development phase;
- Deciding how to depict climate change and variability in a way that related to the ecosystem services of concern;
- Developing and implementing plans to engage appropriate stakeholders;
- Implementing a model development and integration phase; and
- Communicating results in a variety of forums and formats.

Each project manager guided the project based on the particular expertise he or she brought to the table. Ecologists led the San Pedro and Maryland case-study teams, and many of the technical advances were related to methods for simulating important ecological processes. A hydroclimatologist led the Sacramento study, and much of the effort on that study—particularly in the initial stages of the project—was devoted to developing an innovative technique to downscale Global Circulation Model results to the regional scale.

One issue faced by all three case-study teams was the need for several "keystone" skills, especially expertise in interpreting climate change scenarios, working with stakeholders, and evaluating and communicating uncertainty. To address one area of expertise lacking from some of the case-study teams, Dr. David Yates, the hydroclimatologist who led the Sacramento case-study team, acted as an informal consultant to the other two project teams in developing their climate scenarios. Another missing area of expertise was addressed by the Sacramento case-study team through the addition of an expert in stakeholder processes who conducted an evaluation of stakeholder needs, processes, and decision points related to climate change impacts information. The extent to which each case-study team expressed the need for a set of "key" skills raises the question of whether future watershed assessments would benefit from some degree of standardization in terms of expertise, methods, or tools.

3.1.1.2. *Recommendation #1—Provide Keystone Capabilities and Tools to Project Teams*

As noted earlier, there were several areas where all three case-study teams expended considerable effort on similar tasks. It is reasonable to expect that other watershed-level assessments would need to undergo similar processes. When conducting similar assessments in the future, several useful keystone capabilities and tools to include are as follows:

- **Tools for converting GCM output to watershed modeling input**. The case-study teams all had an initial focus on reviewing and interpreting GCM runs to develop their climate scenarios. GCMs simulate temperature and precipitation on short time steps ranging from 15 minutes to half a day. Such data are often stored as averages over longer periods of time (often monthly), because of data storage constraints. Most hydrologic processes require daily (or even hourly) inputs over a finer geographic scale and need to be downscaled on both a temporal and geographic basis. GCM runs are also available for many different combinations of emission scenarios and climate sensitivities, and it can be daunting to choose among the scenarios. The lesson learned from these case studies is to provide expertise to future project teams to aid in selecting, interpreting, and downscaling

GCM output. Future assessments could use an existing tool or develop a new tool for handling climate information. For example, one tool developed by EPA is the BASINS Climate Assessment Tool. This tool provides users flexible capabilities for creating climate change scenarios that allow users to quickly assess a wide range of "what if" questions about how weather and climate could affect their systems using the Hydrologic Simulation Program FORTRAN watershed model (U.S. EPA, 2009), and provides case studies of potential applications (U.S. EPA, 2012).

- **Tools to develop or apply trend analysis of precipitation and hydrology to complement GCM output**. A simple trend analysis of climate variables may be a complementary approach to create future scenarios (Denault et al., 2006). Although conventional precipitation and hydrology analyses of intensity, duration, and frequency are based on the assumption that there is no underlying trend in the record (i.e., that a record from 100 years ago has equal relevance to predicting tomorrow's conditions as a record from 100 days ago), several new powerful statistical techniques exist to evaluate trends and could be made available to watershed researchers to complement GCM output (Denault et al., 2006).

- **Build capacity in keystone skills**. Project teams could benefit from having access to expertise in key areas such as climate scenario development, habitat suitability analysis, stakeholder facilitation, and uncertainty analysis and communication. To the extent that a set of assessments begin and end with similar inputs and outputs, it may streamline assessment processes to provide access to such experts.

For all of these keystone capabilities and tools, the benefit of providing them to the watershed case-study teams would have to be balanced against the objective of building broad-based technical capacity and testing alternative approaches, which argues for less, rather than more, concentration and standardization of expertise.

3.1.2. Research Design, Case-Study Results, and Future Applicability

3.1.2.1. *Findings (Research Design)*

All three case-study teams developed approaches that relied on linking a chain of submodels to simulate physical, hydrological, geomorphologic, and ecological components that ultimately related to ecosystem services. All three of the case-study teams also reported challenges in coupling the model elements.

The Maryland case-study team invested considerable effort in linking submodels and developed a paper on the topic (Nelson et al., 2009). The San Pedro case-study team pushed the state of the art in several of the individual submodels, but those submodels remained largely discrete and required considerable effort to provide working interfaces such that the outputs of an “upstream” module could be used as inputs for a “downstream” module. The Sacramento case-study team started with a preexisting modeling framework that linked hydrology and water management. The Sacramento case-study team invested in improvements in the model’s ability to incorporate climate scenarios and represent surface water-groundwater interactions.

Geomorphology took on a central role in two of the three studies (San Pedro and Maryland). One of the key aspects of climate change—more intense precipitation as well as longer dry periods—translates to higher high flows and lower low flows in the hydrographs of streams. These changes, in turn, affect the processes that create transitional ecosystems vital for certain avian species. They also govern sediment transport and stability, which affect spawning success for fish. The resulting changes in avian and aquatic habitat were key drivers in the San Pedro and Maryland studies.

With the exception of the Sacramento case-study team’s modeling framework, methods of linking were primarily functional, in which the models were not significantly modified, but calculations were coordinated, with certain models’ outputs directed to other models’ inputs according to a specified order for the computations. Each of the case-study teams recognized the value of linking these types of models and expressed an interest in integrating additional models to add more dimensions to the studies.

These linked sets of models were helpful from both the scientific and decision support points of view. Modeling system behavior helps to explore uncertainties and identify critical system interactions and sensitivities. Fully integrated models may also facilitate assessments of a broader array of decision-relevant questions using multiple scenarios. For example, the Sacramento case-study team’s assessment framework helps decision makers evaluate a number of different adaptation strategies to identify tradeoffs among important ecosystem services. This framework, known as WEAP (Yates et al., 2009), is able to provide integrated water resource management support to the Sacramento region, to the state of California, and to other regions of the country.

3.1.2.2. *Findings (Case-Study Results)*

As noted earlier, a “portfolio approach” was used to select case studies and commission assessments in three distinctly different watersheds with differing ecosystem services, scales, and decision-making processes. The Maryland case-study team separately quantified the effects of land-use change and climate change, but they determined that it was unclear which stressor had a larger impact; they found that each contributes to the same impacts but in slightly different proportions. Land-use change provides more sediment due to increased construction and increased impervious surface, and climate change causes more increased storm flow, disturbances to the streambed, and variability in conditions than land use. Effects on ecological processes are thus generally negatively influenced by the projected climate and land-use changes and, when the stressors are combined, predominantly negative effects emerge. (Nelson et al., 2009; Nelson and Palmer, 2007.)

The Sacramento and San Pedro case-study teams did not separate the effects of land-use change and climate change but expressed interest in evaluating these stressors independently in the future. Sacramento researchers noted that they would like to systematically separate ecosystem stressors given their particular challenge of moving water out of irrigation and into the urban environment (U.S. EPA, 2005). The San Pedro case-study team noted that climate change is not as significant a stressor as aquifer depletion; however, when both stressors are applied together, there is a synergistic effect. The San Pedro case-study team also acknowledged that isolating the effects of land-use change and climate change in the future could provide information about runoff and surface flow (U.S. EPA, 2005).

The Maryland case-study team found that up to three-quarters of the fish species would be highly stressed under the combined effects of land-use change and climate change and that this outcome could be mitigated by maintaining riparian buffers and decreasing urbanization. The Maryland case-study team also concluded that not all ecological processes were negatively influenced by projected climate change and land-use change; however, when they are combined, predominantly negative effects emerge. In addition, low-flow modeling indicates that future precipitation trends will influence hydrologic and ecological processes more than future temperature trends, and the frequency of low flow events of a given magnitude will increase under future climate and land-use changes (Moglen et al., 2006).

The San Pedro case-study team found that among their five climate scenarios, the warmer drier scenario could exacerbate current water use conflicts between the human and natural ecosystems of the Upper San Pedro basin and could accelerate the decline of cottonwood-willow gallery forests. A wetter future could partially mitigate the impacts of human water use (Dixon et al., 2008).

The Sacramento case-study team addressed the issue of adapting to climate change by looking at three future alternatives including a simulation without adaptation, a simulation with increases in irrigation efficiency, and a simulation with improved irrigation efficiency and shifts in cropping patterns related to the simulated status of available water supplies. The results showed that improvements in irrigation efficiency led to a decline in supply requirements. When coupled, the effect of improved irrigation efficiency and a dynamic crop pattern was a decrease in water supply requirements. In addition, the study showed that the management structures and practices that adversely affected the fish populations historically may provide an opportunity to alleviate some of the future impacts of climate change (such as changes in the schedule of water releases from dams) (Yates et al., 2006).

3.1.2.3. *Findings (Future Applications)*

All three of these place-based assessments provided impacts information that will be useful to specific decision makers as they develop management responses. Each case-study team was able to examine the interaction of climate change with other stressors already present, particularly land-use change, and was able to conclude that climate change will exacerbate those effects. Where stressors were examined separately by the Maryland case study, results revealed that the interactive effects were strongly negative and more apparent than when the stressors were considered separately.

Even though there are many distinctions in the hydrology and bioclimatology of the case-study sites and differences in the assessment processes used to achieve specific objectives and endpoints, findings emerged that can be extrapolated to other watersheds and regions and that can shape strategies for designing processes for similar assessments. The main ways that results are more broadly useful are as follows:

1. Extrapolation of the results themselves: individual results may be extrapolated for some watersheds to similar systems. For example, results from the San Pedro can be extrapolated to other riparian ecosystems in the southwestern United States that rely primarily on runoff during the summer “monsoon” season; Maryland results can be extrapolated to other Piedmont rivers (such as those in North Carolina); the interactive

effects of climate and land-use change can be generalized to other watersheds, as well as the results that climate will exacerbate existing effects of stressors.

2. Transferability of models to other watersheds: the San Pedro model, although it is specific to riparian systems in the southwestern United States, could be applied to other similar ecosystems, and the riparian evapotranspiration submodel could also be transferable to specific types of wetlands, such as the Everglades; the WEAP modeling system may be the most transferable because the intrinsic logic behind WEAP is universal—it could be produced for other locations with site-specific data over a relatively short time frame (and has been, as of the release of this report—see http://www.weap21.org/index.asp?doc = 05).
3. The methods used to link process models across disciplines may be used by other project teams and in other geographic regions of the country.
4. The insights gained about the assessment process, such as the standardization of methods for climate scenarios, stakeholder processes, and other topics described below, will be helpful to any research institution seeking to produce useful climate impacts information for decision makers (see Recommendation #2 below).

3.1.2.4. *Recommendation #2—Emphasize Model Linkages*

Given the multidisciplinary nature of these projects and the need for project teams to develop new modeling capabilities to analyze climate change impacts or opportunities for decision support, one of the key challenges is to facilitate smooth links between submodels. This was one of the most difficult challenges for the case-study teams to overcome.

Although “systems thinking” may be considered the norm for conducting watershed assessments, it may not be sufficient for assuring seamless integration of models. Combining a conceptual framework of the complete system with an information technology perspective to plan the detailed integration of modeling components may be necessary for “seamless” coupling. There are trade-offs between setting up an IT-intensive interface for linked models versus a “hand-crafted” solution. Regardless of the approach taken, more design work done up front to clearly define inputs, outputs, and interactions among submodels may help to avoid scale-related integration issues.

3.1.3. Complexity of Varying Spatial Scales in Watershed Assessments

3.1.3.1. *Findings*

Each case-study team worked at a variety of spatial scales, a result both of the phenomena they were investigating and the scale at which decisions are being addressed.

The case-study team investigating small watersheds in Maryland worked at a subwatershed scale (13−28 mi^2), in part because urban growth is regulated at the county-level. Individual parcels of land rather than pixilated representations were represented in this analysis, and surrounding land uses were fed back into subsequent land-use change dynamics for each parcel.

The San Pedro case-study team examined the upper portions of the San Pedro basin (2,500 mi^2), where most of the remaining perennial or near-perennial river reaches exist, making this stretch of greatest importance for the ecosystem service addressed in the study: the maintenance of avian habitat. Model representations were limited to plot-scale information, however, meaning that the simulations were not run simultaneously for the entire landscape but only for certain representative patches within it.

The Sacramento River Watershed study worked at the basin scale (42,000 mi^2) but designed the study modularly, so that smaller subbasins that performed ecosystem services of particular value (such as Chinook salmon spawning) were nested separately within the design, and stand-alone results could be produced for those areas. The primary decisions being addressed here, including water allocation and the balance of competing legislative and regulatory authority, occur at the state-level, and, consequently, it was necessary to consider the watershed as a whole.

One of the challenges addressed by all three case-study teams was that available data may not be suited to the questions under consideration. For example, the geomorphologic processes that shape channel migration act at a localized level within a stream reach, but information on the hydrologic and geologic factors that control these processes may be available only on a much broader scale. The case-study teams dealt with this issue by developing scenarios and scaling up their results for sample situations to the larger watershed.

Another important scale issue that the case-study teams addressed was the delivery of ecosystem services at varying scales and with different levels of “connectedness” to other resources outside the study area. For example, in San Pedro, with its focus on migratory neotropical birds, the birds are dependent on the availability of suitable habitat at other locations and other times. Similarly, in Sacramento, one of the key endpoints—instream flows to support salmon—is necessary but not sufficient for sustaining “threatened” and “endangered” salmon populations. Climate change could affect the other critical resources needed to support these populations, but to keep the scope manageable, the case-study teams assumed that conditions outside their study’s boundaries were essentially static.

Cash and Moser (2000) suggest that the multiscale nature of global environmental problems poses fundamental challenges to how both assessors and managers work and interact, including matching the (spatial and temporal) scales of biogeophysical systems with scales of management systems; matching the scales of the assessment with the scales of management; and accounting for cross-scale dynamics in both natural systems and institutions. All three case-study teams experienced these challenges.

3.1.3.2. *Recommendation #3—Carry Out Assessment Activities at Multiple Scales*

One approach to consider when conducting a watershed assessment is to carry out assessment activities at multiple scales. Multiscale approaches provide more useful information than a focus on any one single scale (e.g., Alessa et al., 2008; Vincent, 2007; Sullivan and Meigh, 2007, among many others). Benefits of this approach include: (1) better problem definition, as a single-scale assessment may focus on issues most relevant to that scale; (2) improved analysis of scale-dependent processes, cross-scale effects, and causality; (3) improved accuracy and reliability of findings; (4) improved relevance of problem definition and assessment findings for users and decision makers; and (5) increased ownership by the intended users (MA, 2005).

One specific method that may be used within a multiple scale approach is the integrated indicator approach. This involves aggregating vulnerability indicators, sometimes multiple layers of indicators, into a representative index or indices to represent the vulnerability of the target region (see Hurd et al., [1999], and U.S. EPA [2011] for examples for water resources). The integrated indicator approach can provide a simple way to combine biophysical, social, economic, and environmental data to produce a single value representing vulnerability, allowing a systematic evaluation of individual and sets of indicators, and to compare geographical or political units. It can also be useful at the screening level to identify candidates for more extensive vulnerability analysis. Screening-level indicator applications provide information useful at multiple scales: (1) they can provide a national-level picture of how vulnerability varies across the country; (2) they can limit the number of resource-intensive local-scale assessments needed; and (3) they can foster discussion at the local level of the suitability of the ranking for the local community which may, in turn, provide useful information in national policy discussions.

3.1.4. Estimation and Communication of Uncertainty

The first section below discusses sources of uncertainty, and the second briefly reviews issues that arose when communicating uncertainty to stakeholders.

3.1.4.1. *Findings (Type and Extent of Uncertainties)*

There are three sources of uncertainty that could affect case-study results, including uncertainties about the forcing of climate data, model structure, and model parameter values. Following the usual practice, climate change uncertainties were addressed using climate change scenarios. Three different approaches were used by the case-study teams: (1) multiple GCM realizations (assuming that more common results indicate more probable outcomes), (2) Monte Carlo-type analysis (Yates et al., 2003), or (3) the use of historical data to bracket the range of variation for particular climate parameters.

Uncertainties about land-use effects, hydrology, and geomorphology were the primary sources of structural and parameter uncertainty. For example, the Maryland researchers found that land use was quite sensitive to regulatory changes, population growth, and income changes. Once the potential land open for development has been developed, the possible responses by landowners is unknown, but possible outcomes are intensification of developed areas or reclassification of previously undeveloped land and further landscape alteration. Additionally, while land use may be predicted on a large scale with some degree of certainty, the idiosyncrasies of individual land owners and managers may never be anticipated with complete predictability. Other sources of uncertainty in the Maryland study included a lack of knowledge regarding the effects of the interactions of multiple stressors in streams, the biology of understudied fish species, and predictions of habitat suitability.

Hydrological responses to changing land use were identified by both the Maryland and Sacramento case-study teams as primary contributors to overall model uncertainty. Geomorphological responses were another large contributor to uncertainty, particularly in the San Pedro watershed, for which management goals are predicated, in part, on the occurrence of transitional ecological states. These transitional states are highly dependent upon sporadic hydrological events such as flooding, which transfer to the ecosystem through their geomorphological effects. The creation of unvegetated areas on channel islands or river banks by floods allows colonization by plants that would otherwise be unable to compete with the established plant communities and, thereby, increases overall habitat diversity. With time, these colonizing plants are replaced by more stable assemblages, and floods create new unvegetated areas. Any one plot may show little change, but over a larger area, the patchiness of habitat types allows high avian diversity to be maintained. In general, it is more challenging to predict and monitor processes associated with unusual or extreme events and transitional conditions, and analyses of this type tend to be more uncertain than those dealing with processes that are driven by average conditions.

3.1.4.2. *Findings (Methods for Estimating and Communicating Uncertainty)*

In communicating to stakeholders the uncertainties associated with climate and land-use change effects on ecological and water resources, a concern of the researchers was that uncertainty ranges would undermine the possible contribution of results to the decision-making processes. At issue was whether managers would be willing to place confidence in results that are presented as uncertain. The uncertainties could be used to justify setting aside the results, particularly under conditions in which resources are limited and more pressing matters demand immediate attention and action.

Another issue involved determining the way in which uncertainty analysis might be conducted to be most useful to stakeholders. The Sacramento case-study team found that their stakeholders were interested in “stylized” scenarios. For example, the El Dorado Irrigation district currently uses the worst 3-year drought on record as the basis for developing drought plans. To be responsive to and consistent with their existing planning guidelines, the Sacramento case-study team developed alternative scenarios such as a 4-year drought of similar magnitude to the 3-year drought but one that is also 2°C warmer.

The project teams noted that it would be helpful to have guidance on how to characterize and communicate uncertainty results. In addition, several noted that it would be useful to be able to compare climate change-related uncertainty to uncertainty from other, more familiar sources relevant to long-term water resource decision making, (e.g., population, land-use change, per capita water demand).

3.1.4.3. *Recommendation #4—Require Explicit Uncertainty Analyses as Part of any Assessment*

Future assessments should consider carefully how to address uncertainty within the decision-making context. The data available and the degree of uncertainty related to the decision at hand may require alternative approaches to a classic uncertainty analysis (Groves and Lempert, 2007). Several approaches include sensitivity and scenario analyses, and scenario planning. For the purposes of this report, a scenario may be defined as a plausible description of how the future may develop, based on a coherent, internally consistent set of assumptions about driving forces and key relationships (Morgan et al, 2008; IPCC-TGICA, 2007).

Analyses that evaluate the sensitivities in a system should be designed based on the questions being addressed by an assessment. Approaches such as examining the scientific literature or eliciting expert judgment may be sufficient to address certain questions. Useful, though limited, information may also come from observed responses to historical climate variability. However, analyses of more detailed scenarios may be required in other situations, such as those in which multistressor impacts are being assessed, or variability is outside the range of observations. Scenarios may also be developed in which climatic drivers are systematically and incrementally changed. In all cases, the emphasis is on exploring the behavior of the system in order to identify the following:

- Significant responses of endpoints to changes in some particular drivers and not others
- Asymmetrical responses of endpoints (e.g., large sensitivities to dry conditions but little response to wet conditions in response to changes in precipitation,)
- Other nonlinear behaviors, such as large, disproportionate responses of endpoints to drivers in certain portions of the range

- Thresholds above or below which particularly severe system impacts occur (e.g., the amount of climatic warming required to raise water temperatures in a stream to the point that a cold water fish species cannot reproduce and survive)

Techniques for watershed studies that address uncertainty are available from many sources (e.g., Johnson and Weaver, 2009; Groves and Lempert, 2007; Moss and Schneider, 2000; Hession et al., 1996). The goal of these approaches is to support improved decision making by allowing more complete consideration of outcomes and their implications, and to highlight the tradeoffs among alternative decisions. Rather than avoiding discussions of uncertainty, uncertainty needs to be recognized as a crucial component of any assessment that is intended to inform decision making.

With respect to communicating uncertainty, conversations with stakeholders can be useful and informative rather than daunting. For example, discussing with stakeholders those management options that are robust over a wide range of potential future conditions can relieve the burden they may feel to identify “the optimal solution” for a single most-likely future. Climate change uncertainty may also be communicated using comparisons with more familiar sources of uncertainty. For example, long-range water resource plans generally make assumptions on population growth, changes in demand for key uses (e.g., agriculture), and changes in per capita demand. While these assumptions are sometimes heroic, they are nevertheless familiar (unlike climate change-related factors). Comparing sources of uncertainty may help illustrate the similarities between other long-term decisions made in an uncertain context and climate change uncertainties, perhaps reducing reluctance to incorporate results into decision making. Regardless of the specific approach taken to analyze uncertainty, future watershed assessments need to plan for conducting such analyses and then execute the plan.

3.2. STAKEHOLDER PROCESSES

Each case-study research team approached stakeholder inclusion somewhat differently, though a number of features and impressions were common among them. In general, the case-study teams relied on existing stakeholder relationships and processes. Interactions with these stakeholder groups were moderate in their frequency, scope, and intensity. The information flows were primarily unidirectional, from the case-study research teams to stakeholders—although stakeholders were given opportunities to provide input on each study’s endpoints. A kickoff meeting was a common feature among all of the case studies. After that point, the Sacramento case-study team continued with structured elicitation of stakeholder input. Stakeholder involvement for the Maryland and San Pedro case-study teams was generally less structured and more opportunistic after the initial kickoff. All case-study teams found that stakeholder involvement can be a resource-intensive exercise. This and other challenges the case-study teams faced in engaging stakeholders are discussed in more detail below.

3.2.1. Defining and Identifying Appropriate Stakeholders

3.2.1.1. *Findings*

For each case-study team, the concept of stakeholder engagement initially included a wide array of individuals from decision makers to nongovernmental organizations to interested citizens. Over time, the case-study teams became more sophisticated in their understanding of the types of stakeholder interactions that were productive and refined their processes to reflect a targeted and focused approach. Without such targeting, the case-study teams found that continuing a meaningful dialogue with a broad array of stakeholders could be paralyzing to the assessment process.

The Maryland case-study team initiated a broad-based introductory meeting for stakeholders. Professional, academic, and EPA personnel were the initial contact points for assembling this group. The goal of the meeting was primarily information dissemination from the researchers to interested parties. Subsequently, the case-study team developed a close and interactive relationship with the Montgomery County Department of Environmental Protection that led to an exchange of data and some collaboration and incorporation of researchers' findings into a wider planning context. Interactions were focused primarily on this stakeholder group throughout the rest of the assessment process (U.S. EPA, 2005).

Researchers in the Upper San Pedro Basin began work in a setting that had an active stakeholder group—the Upper San Pedro Partnership (USPP). The USPP is a consortium of local, state, and federal government organizations, Fort Huachuca Army Base, businesses, citizens, and conservation groups. The USPP works to develop decision support tools for analysis of alternative water management regimes, and members of the case-study team became participants in this ongoing process. Additionally, their affiliation with the Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA)—a National Science Foundation-supported research center at the University of Arizona—provided them with indirect access to stakeholders.

The San Pedro case-study team made study results available to the USPP and SAHRA and their stakeholder organizations.

The case-study team working in the Sacramento River Watershed sought to identify stakeholders engaged in ongoing decisions regarding water allocations. The Sacramento case-study team started by assembling a Technical Advisory Panel formed of regionally-based academics from the physical, ecological, and economic sciences. Meetings with this Panel occurred at the beginning, middle, and end of the investigation to gather input on other experts to consult with and to refine the development and application of their modeling framework. Additionally, a consultant was brought on board the Sacramento case-study team to interview other high-level water and ecosystem management organizations in the Sacramento area in order to make strategic recommendations regarding potential applications of their research. This effort resulted in meetings with several other decision-making organizations and follow-on analyses to support their decision processes. The case-study team found that the key to establishing working relationships with stakeholders was to demonstrate that their work was relevant to the decisions at hand, scientifically credible, and legitimate as an approach to climate change analysis. The Sacramento case-study team also stressed the importance of finding an advocate among the participating stakeholders. One person who acts as a champion for collaborating with researchers and participating in the assessment process can help sustain and facilitate the relationship (U.S. EPA, 2005).

3.2.1.2. *Recommendation #5—Build on Existing Stakeholder Relationships, Target Selection, and Establish Credibility*

Research case-study teams already work with stakeholders in many areas and have developed long-standing relationships with decision makers, and can build on these existing relationships when seeking input from stakeholders. Strengthening existing relationships will take less time and resources than trying to establish new relationships with numerous stakeholders. Such existing stakeholder groups have also demonstrated a sustained and ongoing interest in an issue or issues for which they were formed, and if those issues are related to the focus of a new case-study research team’s assessment, than they may bring that sustained engagement to those issues as well. Further, existing relationships can open doors to meeting and collaborating with new stakeholders who may be similarly interested in study findings. In much the same way that the selection criteria for this set of projects involved availability of existing data, future projects may also benefit from a selection criterion to evaluate availability of existing relationships.

Streamlining and focusing stakeholder-related efforts is necessary and desirable. Effective stakeholder interactions are those that produce results that directly support policies. The case studies showed that stakeholder relationships may not need to extend to all potentially interested members of the lay public; instead, they should target only specific decision makers who have an identifiable stake in the study's goals. Working closely with decision makers to supply information based on their needs and demands may also help facilitate later transferability of results and processes because the questions being addressed are likely to be relevant to decision makers elsewhere. An additional advantage when targeting and engaging stakeholders interactions might be derived from developing collaborative *working* partnerships with members of the decision-making body where possible, to gain their interest and trust in the assessment results. A working partnership builds technical capacity within the decision-making body that increases the likelihood of climate change impacts being considered beyond the particular assessment.

When beginning to engage stakeholders, the first step may need to be establishing credibility—credibility of the science underlying the methods and models to be used, and credibility of the planned analysis to be useful to the decisions at hand. The public debate on climate science has been polarizing, and its relevance to issues on the ground difficult to discern for the average person. So credibility, or the level of trustworthiness and authority that stakeholders perceive a project team has related to the work at hand, is key to producing results that are used in a decision-making process. The project team must set aside time to demonstrate to decision makers that their models have been reviewed and validated by others, experts in the field corroborate the methods and analytical approach, and hard evidence exists to support all of the above. Without credibility, the results may be easily dismissed.

3.2.2. Maintaining Stakeholder Processes

3.2.2.1. *Findings*

Stakeholders engaged in each case study had diverse views on which services should receive highest priority for study resources. Case-study teams had to balance those competing stakeholder interests with their own research interests. The case-study team members recognized the dilemma that the primary focus of many scientists—credibility—requires academic achievements that can come at the expense of spending time with stakeholders to prove the credibility and relevance of their work to decisions. While stakeholder interactions increase the likelihood of a project's usefulness, maintaining those interactions can be onerous and resource-intensive, and thus, come at the expense of other priorities. The inverse of this challenge is also true: managers do not necessarily recognize the relevance of research (especially research on long-term problems), often deeming it merely an academic exercise with no application to their pressing concerns.

Climate change is a particularly acute example of this situation. All research case-study teams reported at the time of these studies that climate change was not recognized by managers and decision makers as a primary concern that must be addressed within a relevant timeframe. Similarly, it may not be clear to them that investing time in climate change-related work could help in addressing more immediate concerns. Thus, neither side (researchers nor stakeholders) may be willing or prepared to participate in collaborative exercises that require sustained interactions over the lifetime of a study, especially a study with results that do not seem relevant in the near-term.

3.2.2.2. *Recommendation #6—Incorporate Incentives for Mutually Beneficial Results*

Sustaining researcher and stakeholder interactions throughout an assessment process will require creating incentives for both parties. Example principles that need to govern a project team's approach to a study may help ensure that both stakeholders and researchers commit to long-term engagement. These principles include the following:

1. **Empower stakeholders:** Stakeholders need to have defined roles and responsibilities in the study process, with representation rather than marginalization of the various interests. Stakeholders' views and contributions should be considered, responded to, and if appropriate, integrated into an assessment, thus making the participatory approach a means of encouraging contribution and cooperation among the different stakeholder groups. Seeking a collaborative role (working partnerships) for stakeholders, as mentioned in the previous recommendation, is an effective way to empower them and ensure continued engagement. Participatory needs assessment, collaborative research, and mutual exploration of results represent "best practices" for stakeholder processes.

2. **Motivate stakeholders:** As mentioned in the previous recommendation, case-study teams need to demonstrate how their analysis will support effective solutions to real problems (a component of establishing credibility) and how stakeholder participation in the process will add value to the results. Elicitation of all views and timely and thoughtful consideration of them, along with responses that address their expressed needs and concerns will help to increase their motivation.

3. **Be transparent and communicate often:** Case-study members need to be accessible and communicate in plain language their methods, approach, results, assumptions, uncertainties, etc. throughout the assessment to build stakeholder awareness and support. They must also provide stakeholders access to results and develop their capability to share the information with their own organizations and with broader stakeholder audiences. This will widen the sphere of support for the study and its results. Information sharing can happen through printed materials (such as research reports, workshop proceedings, presentations, fact sheets, maps, and posters) or other more innovative media (such as audio or visual podcasts). These materials need to be designed with all of the relevant audiences in mind, because these audiences may be as disparate as high level politicians and citizen farmers.

4. **Be flexible and innovative:** The project team needs to be flexible and innovative with respect to responding to stakeholder priorities and interests as assessment goals, targets, methods, and endpoints are established. Flexibility can stimulate the design and implementation of innovative analytic approaches and solutions and encourage continuous improvement in the assessment process.

5. **Recognize and reward stakeholders:** It is key that the case-study team recognize and reward exemplary efforts by stakeholders to engage and contribute to an assessment process and promote or use results. This may be done in many ways, but should include feedback to the stakeholder's organization on the contribution a member is making to the assessment process.

6. **Track success:** Develop indicators to track the success of the engagement process. Then note responses to engagement incentives to understand what works best and what needs to be improved. Indicators may include the number of meetings attended, the continuity of participation of individuals and groups, the degree of information shared by stakeholders to those beyond the established members, number of conflicts that arise, and amount, degree, and type of feedback received from members. Additionally, evaluating other groups' stakeholder processes may provide valuable information that can highlight potential barriers, opportunities, and practical lessons that a case-study team can use in its own processes.

7. **Build local capacity:** To make the study useful beyond the results themselves, case-study teams should consider building local capacity to conduct their own analyses through providing technical assistance and training. If any stakeholders are interested, providing such assistance will engender good will, increase the capacity of communities to respond to climate change, and catalyze stakeholder participation in any future studies.

3.3. RELEVANCE OF IMPACTS TO DECISION MAKING

The Maryland and San Pedro case-study teams focused primarily on conducting impact assessments—determining the effects of global change (including climate change and land-use change) on water quantity and quality and the consequences for aquatic ecosystems. These assessments made significant contributions by linking multiple models to better understand stressor interactions and responses. Although assessment results did not immediately and directly inform specific decisions, they provided a foundation on which subsequent work can build to inform future decisions. Those decisions will have to be based on an evaluation of alternative policies that prove to be robust across a wide variety of potential future climatic changes and ecological responses.

The Maryland case-study team found that decision makers at the county level (Montgomery County) were very interested in the land-use change component of the case study. Montgomery County officials were focused on problems they are facing in the immediate term and took a special interest in the findings regarding nutrient concentrations in various streams. They were pleased to see evidence that riparian buffers have a definite impact on those concentrations. They have used the study findings to validate research they have in progress and recommendations they have already put forward. The Maryland case-study team's findings also reveal the importance of considering climate change. One important area in which to do so is stormwater management. Facilities that are being built or retrofitted need to account for potential changes in the intensity of future rainfall events, because such events could affect their performance (U.S. EPA, 2005).

The San Pedro case-study team's findings were used by the Bureau of Land Management (BLM) and water resource managers to assess flow rules for reservoir releases from a dam in the middle San Pedro area. The San Pedro case-study team's results regarding loss of water in the system led to a BLM decision to reintroduce beaver in an attempt to impound and detain water rather than letting it flow downstream. However, the BLM decision is unusual. In general, the San Pedro case-study team noted that a number of obstacles exist for the incorporation of study findings into the decision-making process, including the uncertainty inherent in climate change projections, other factors that take precedence in management decisions, and sometimes politics (U.S. EPA, 2005).

With a second phase of funding, the Sacramento case-study team identified key water-related decisions and then tailored their analytical work to meet the needs of decision makers. They consulted stakeholders to develop a list of ongoing decision-making processes in the California water system that might be sensitive to climate change. The list was then narrowed to include only decision-making processes that met three criteria (Purkey et al., 2007):

- The success of a project to be implemented would be strongly influenced by hydrologic variability.
- The investment in a project would be substantial enough to merit the consideration of climate change impacts.
- Some segment of the stakeholder community was concerned about the potential impact of climate change on the project.

This second round of funding enabled the Sacramento case-study team to produce results for the following decision-making processes: (1) the Integrated Regional Water Management Plan for the Consumes, American, Bear, and Yuba watersheds; (2) the California Department of Water Resources' 5-year water planning process (Bulletin 160); (3) an assessment by several water utilities generating hydropower in the American river basin of how vulnerable they are to climate change and their ability to meet more stringent inflow water demands; and (4) the 2006 Climate Action Team Final Report to Governor Schwarzenegger and the California Legislature.

3.3.1.1. *Recommendation #7—Design Selection Criteria to Maximize Decision Support*

One of the recurring themes in this report is that the case studies were quite thorough and innovative in assessing climate change impacts but were somewhat more limited in providing direct decision support. It may be because selection criteria were dominated by choosing sites with a good foundation of existing data and models so that impacts could be assessed as efficiently as possible. For future watershed assessments, it may be useful to modify the selection criteria to emphasize case studies (1) where it is clear that decisions are being made that are sensitive to climate change, and (2) where there are existing relationships with decision makers that would enable the project team to provide relevant decision support products.

Another factor that should be reevaluated in terms of selection criteria and study design relates to scale. The research case-study teams noted that there were some mismatches between available data versus the scale of data needed to support assessments and decision-making processes. All three case-study teams were able to bridge the gaps. Nevertheless, in developing a strategy for future work, it would be useful to consider the scale at which GCM and watershed-level information are available, the scale at which key endpoints are assessed, and the uncertainty introduced by bridging the gap, to assure that it will be feasible to produce good science and sound decision support.

4. CONCLUSIONS

The case-study approach yields richness of detail in terms of methods and results, and it propels a research team well up the learning curve on climate change issues. Because conducting case studies requires linking models from multiple disciplines in some fashion to complete assessments and provide useful results, this approach has proven extremely effective in both pushing forward the state of the art of impact assessment and characterizing the potential effects of climate change and land-use change on ecosystem services to support adaptation planning.

It is important to ensure that capacity for doing assessments is in place before the project starts. As discussed in Section 3, there are a number of critical factors that ensure success for impact assessments, including good data, good models, clear goals, appropriate technical expertise, and public awareness of and engagement in the issue. Identifying that these critical success factors are in place before launching an assessment will help determine if there is sufficient capacity to undertake such an assessment.

Assessments may be initiated to achieve a variety of different goals. If the goal of an assessment is to inform specific decisions, then those decisions should be the primary guide for selecting endpoints and processes to be modeled. To leverage limited resources, the assessment community could also think about designing assessments that can inform a broader set of decisions and decision makers in different regions and watersheds with similar goals and environmental issues. The ability to transfer the assessment methodology and model results is more likely if goals are defined upfront and the assessment approach is decision-relevant.

Project teams also need to address uncertainty. However, this can be a difficult task if the expression of uncertainty is perceived by the decision maker to render the results unusable. Understanding how to address uncertainty in an appropriate and meaningful way to inform decision making can be challenging but can be made more tractable by focusing on those uncertainties that matter to decisions and identifying robust management options across those uncertainties.

Moving forward, it may be constructive for case-study teams to develop a formal framework for assuring that assessments are decision-driven, not necessarily by early and frequent exposure to a broad set of stakeholders, but instead by a focus on a narrow set of decisions and stakeholders where the information will be most useful. In addition to adopting the recommendations found in Section 3, case-study teams may also want to use the following questions to help establish assessment priorities:

1. Are the decisions (e.g., about choices of management actions) likely or unlikely to be affected by climate change?
2. If the decisions are likely to be affected by climate change, can they (the particular management actions) be modified/adapted to ameliorate climate change impacts?
3. If the decisions can be modified/adapted to ameliorate climate change impacts, do they have short or long planning horizons, implementation periods, or lifespans?

Decisions, or management actions that are affected by climate change and that can be adjusted to ameliorate impacts present opportunities for effective adaptation, provided the right scientific information can be offered as to how management actions should be modified/adapted. If management actions have short planning horizons and/or lifetimes, than providing scientific information to appropriately adjust those actions becomes less critical than if those same actions are long-lived. Ongoing research and assessments that directly inform such long-lived decisions would thus be particularly useful.

The questions above that are intended to focus assessments on providing key, decision-driven information can build the capacity of decision makers to better respond to global change impacts on water quality and aquatic ecosystems, but there is still much work to be done to understand all of the elements needed to make information as useful as possible. Future projects will afford the opportunity to learn more about how to best address all of the challenges identified in this report (and more challenges that will likely emerge) to improve the usefulness of assessment results.

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